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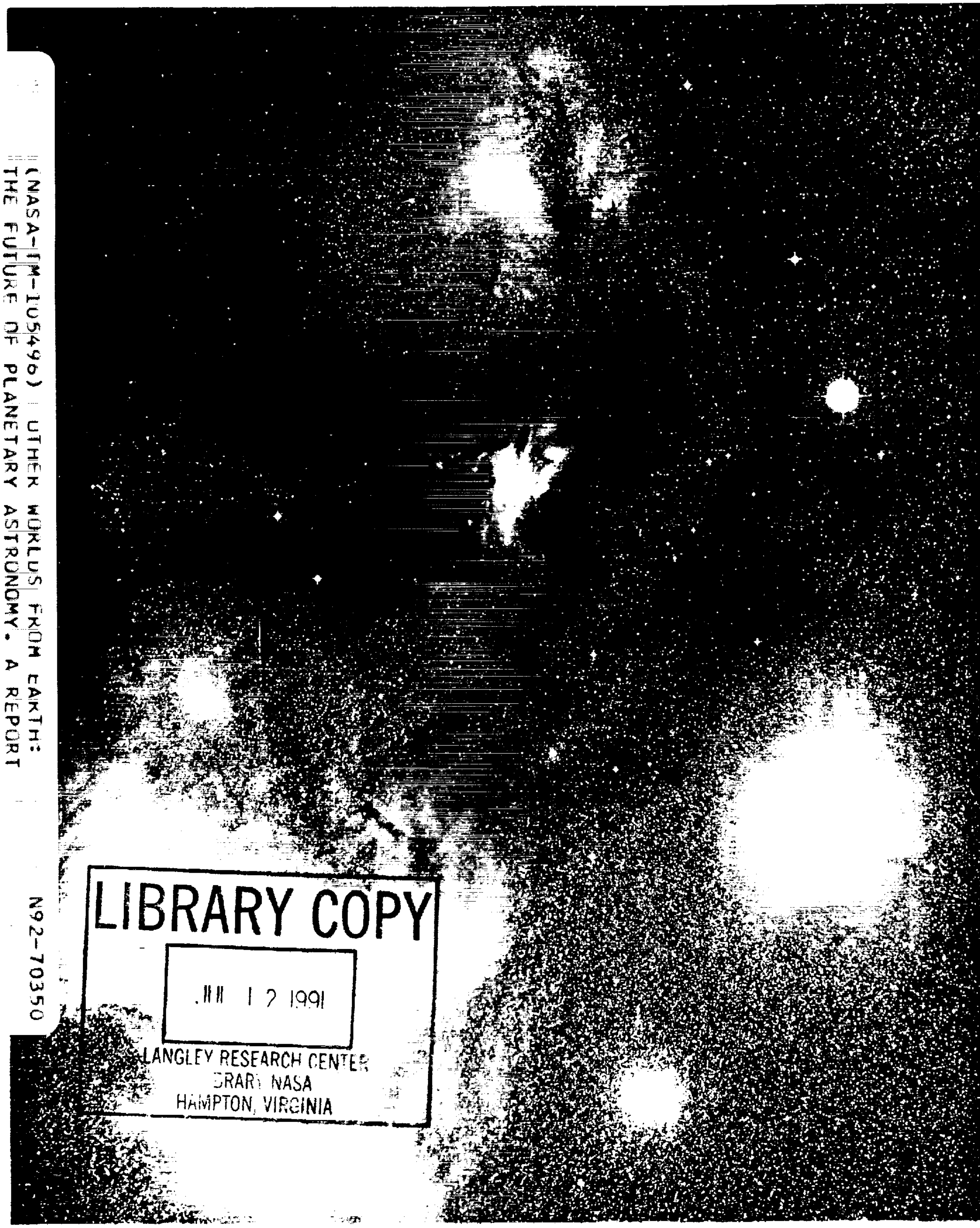
OTHER WORLDS FROM EARTH:
THE FUTURE OF PLANETARY ASTRONOMY

A REPORT OF THE PLANETARY ASTRONOMY COMMITTEE OF THE SOLAR SYSTEM EXPLORATION DIVISION



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Cover: The Rho Ophiuci Dark Cloud contains one of the most extensive collections of nebulae in the sky. Stars in the cloud of gas and dust produce blue, red, and yellow glows. Smaller, yellowish nebulae may indicate that new stars are forming deep inside the dark cloud.

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WASHINGTON, D.C., 1989

Star trails over the Canada-France-Hawaii telescope.

The Planetary Astronomy Committee

DAVID MORRISON *(Chair)* UNIVERSITY OF HAWAII
JURGEN RAHE *(Executive Secretary)* NASA/HEADQUARTERS

MICHAEL BELTON, NATIONAL OPTICAL ASTRONOMY OBSERVATORIES
JAY BERGSTRALH, JET PROPULSION LABORATORY
DAVID BLACK, NASA/AMES RESEARCH CENTER
HENRY BRINTON, NASA/HEADQUARTERS
ROBERT BROWN, SPACE TELESCOPE SCIENCE INSTITUTE
DALE CRUIKSHANK, NASA/AMES RESEARCH CENTER
JAMES ELLIOT, MASSACHUSETTS INSTITUTE OF TECHNOLOGY
SAMUEL GULKIS, JET PROPULSION LABORATORY
WARREN MOOS, JOHNS HOPKINS UNIVERSITY
MICHAEL MUMMA, NASA/GODDARD SPACE FLIGHT CENTER
STEVEN OSTRO, JET PROPULSION LABORATORY
BRADFORD SMITH, UNIVERSITY OF ARIZONA
JOSEPH VEVERKA, CORNELL UNIVERSITY
EDWARD WEILER, NASA/HEADQUARTERS
MICHAEL WERNER, NASA/AMES RESEARCH CENTER

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False-color image of Comet Giacobini-Zinner. Color contours indicate levels of brightness; background stars show as streaks, caused by the comet's motion.

Executive Summary

Planetary astronomy—the study of planetary bodies and phenomena by the remote-sensing techniques of ground-based, airborne, and Earth-orbital observations—signified the beginning of our detailed exploration of the solar system. Even today, in the era of spacecraft missions, astronomical techniques still yield much of the information we have on the composition of the surfaces and atmospheres of most of the planets and satellites. And as we expand our perspective to embrace the search for other planetary systems and to probe the details of star and planet formation, we must rely exclusively on advances in the astronomical discipline.

The Planetary Astronomy Committee was formed in December 1985, to assess the status and health of NASA's planetary astronomy program, and to make recommendations for future pursuits in this endeavor. Specific areas of consideration are the continued characterization and detailed study of the solar system using ground-based, airborne, and Earth-orbital capabilities, and the search for and characterization of other planetary systems. Planetary astronomy was found by the Committee to be a productive research discipline with significant potential for future progress; however, some problems were identified, which must be solved to enhance future work in planetary astronomy.

Historically, planetary astronomy at NASA has played a major role in the direct support of flight missions and, equally important, in providing complementary data that greatly amplify the yield from planetary probes. The NASA Solar System Exploration Division should reaffirm its commitment to Earth-based planetary astronomy as an essential component of a balanced program of solar system exploration. Further, we urge the Solar System Exploration Division to recognize a broad mandate for planetary astronomy, which includes the search for other planetary systems and an improved understanding of the process of planet formation in other systems, as well as our own.

Although planetary astronomy remains a healthy and productive research endeavor, the field has been hard hit recently by high inflation rates and cuts in funding. Since NASA is the predominant source of support for this discipline, fluctuations in the NASA budget can have grave consequences for the entire field. High priority should be given to stabilizing the grants program, reinvigorating existing research groups, and creating opportunities for young researchers to enter the field. Also needed is a renewed commitment to support laboratory studies, theory, and interpretation, in addition to the collection of data.

Access to telescopes and state-of-the-art equipment is essential to planetary astronomy. An instrument development program is needed to take advantage of dramatic recent advances in detector technology, which promise order-of-magnitude improvements in sensitivity and efficiency. An essential enhancement of our capability is represented by the proposed upgrades to the Arecibo planetary radar, which can increase its performance by a factor of 20. Additional flights of the Kuiper Airborne Observatory for planetary projects are also desirable, and NASA should begin to plan for access to the new generation of 6- to 10-meter optical/infrared telescopes now being planned for the 1990s.

The Stratospheric Observatory for Infrared Astronomy (SOFIA) will provide important and unique capabilities for planetary astronomy; its development should be supported, with special attention to studies of ways to improve its image quality to the arcsec level.

The *Hubble Space Telescope* represents another major potential tool for planetary studies, but essential work must still be done to provide the *Hubble Space Telescope* with the pointing and tracking capability to pursue a wide range of planetary projects. Another of the Astrophysics Division's Great Observatories, the *Space Infrared Telescope Facility,* also promises major capability for planetary studies, as well as for advancing our knowledge of the processes of star and planet formation. In addition to the Great Observatories, opportunities should be pursued to use small Space Shuttle payloads, such as Astro, Spartan, and Hitchhiker, for planetary work. Orbiting observatories in the Explorer series will also advance planetary studies, but steps must be taken to ensure that planetary payloads are included within the Explorer Program. In all these cases involving orbiting observatories planned and managed by the Astrophysics Division, it is essential that planetary astronomers participate in planning and development, that the special requirements of planetary astronomy (such as the ability to track moving targets) be considered, and that the Solar System Exploration Division assume a clearly defined oversight role where such spacecraft are expected to include planetary objectives.

In the arena of Earth-orbital astronomy, a number of opportunities exist for international collaboration; examples include the European Space Agency's *Infrared Space Observatory* and the proposed German *Planetary Telescope.* We believe that these opportunities for participating in the programs of other nations in the discipline of planetary astronomy should be pursued.

A major new area for solar system studies is arising as we recognize the opportunity to detect and characterize other planetary systems and to study in some detail the associated problems of star and planet formation. The Solar System Exploration Division should assume programmatic responsibility for these two closely coupled endeavors and should pursue both of them from the ground and from Earth orbit. In this way, we can expect to expand the horizons of planetary astronomy to the much more general questions of the origin and prevalence of planetary systems generally, systems with which our own can be compared.

A variety of techniques now exist that should be capable, with modest technology investment, of providing a definitive inventory of nearby stars for planets of 10 Earth masses (thus including objects ranging from Uranus or Neptune up through Jupiter and into the mass range of the brown dwarfs). These techniques, the most mature of which are astrometry and doppler spectroscopy, can be pursued from the ground and from space in complementary ways. Ground-based doppler spectroscopy at the accuracy level of 10 meters/second is already underway and should detect Jupiter- or Saturn-sized planets if any exist in compact orbits around any of dozens of low-mass stars; such studies should be continued and expanded. Ground-based astrometry from an excellent site such as Mauna Kea can pursue a complementary search for Jupiter- or Saturn-sized planets in larger orbits about dozens of nearby stars with masses up to that of the Sun. To realize the potential of the astrometric technique, however, it is essential to construct a dedicated astrometric facility at a site with the best possible seeing conditions.

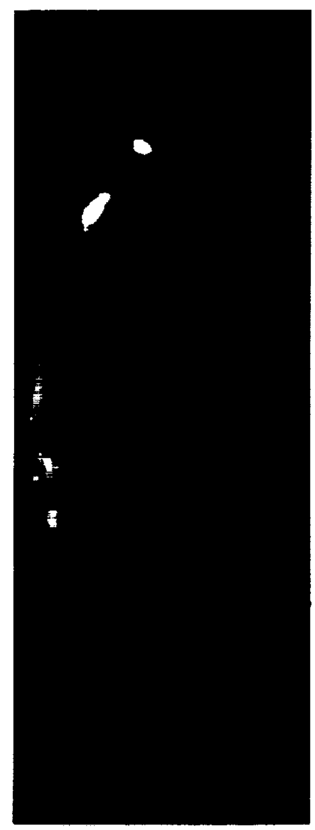
The above ground-based techniques should reveal the largest bodies of a few nearby planetary systems if planet formation is as common a process as is envisioned by present theories of the origin of our own solar system. But such systems may be much rarer than we think, and it is essential eventually to carry out a search at sufficient depth that a negative result will be definitive, as well as to characterize the numbers, masses, and orbits of the planets in systems that are discovered. For this purpose, NASA should pursue development of an advanced astrometric facility in space, capable of measuring stellar positions at a precision of 10 microarcsec and operating for longer than a decade. Such a facility could be deployed on Space Station *Freedom* by the end of the 1990s. In addition, recent advances in super-smooth optics that greatly reduce the scattered light within a telescope offer, for the first time, the prospect of direct imaging of planets around other stars and of studying the properties of their reflected light. In addition to astrometric facilities, NASA should continue the development of these new optical systems for deployment in space. Particularly attractive are options that combine astrometric capability at the 10 microarcsec level with a low-scattered-light imaging system, and we urge that a 1- to 1.5-meter telescope that incorporates this option be studied for possible early deployment on *Freedom.*

Complementary to the search for other planetary systems is an effort to increase our understanding of the processes of planet formation, and also to investigate other possible end points of the condensation of solid material near a star, such as the stellar rings discovered in association with Vega and Beta Pictoris. Low-scattered-light optics and infrared instruments in space offer much promise in the study of circumstellar material. This interdisciplinary field should be supported jointly by the Solar System Exploration and Astrophysics Divisions.

Many of the areas examined by the Planetary Astronomy Committee involve management issues as well as those of a technical and scientific nature. These issues include the need for improved communication and cooperation between the Solar System Exploration Division and the Astrophysics Division and the increased involvement of planetary astronomers in the planning and development of Earth-orbital observatories, including Explorers and small Space Shuttle payloads. We also urge that communications be improved between NASA and the Astronomy Program at the National Science Foundation; although the amount of direct National Science Foundation grant support for planetary astronomers is small, we remain dependent for observing facilities on national observatories such as the National Optical Astronomy Observatories, the National Radio Astronomy Observatory, and the National Astronomy and Ionosphere Center. It is important that the special needs of planetary astronomers be represented in planning and allocating observing time at these telescopes as well. Both NASA and the National Science Foundation should be reminded that planetary targets are often dynamic, transient, and fast-moving, and that if they are not properly planned for, unique observing opportunities are likely to be missed. Finally, in the emerging fields that involve the search for other planetary systems and a more intensive investigation of the process of planet formation, where close cooperation is required between Divisions at NASA, we suggest that special attention and nurturing by the Associate Administrator for Space Science and Applications may be required to ensure the timely pursuit of the new opportunities now available to expand and enrich planetary studies by extending our vision beyond the confines of our own solar system.

The recommendations of the Planetary Astronomy Committee, if implemented, will ensure a robust, vital field of research, now and through the turn of the century. We strongly urge that the realization of the recommendations described in this report does go forward, so that the full potential of planetary astronomy for solar system exploration can be achieved.

Volcanic plumes on Io.



Planetary Astronomy: Discoveries and Advances During the Last Twenty-Five Years

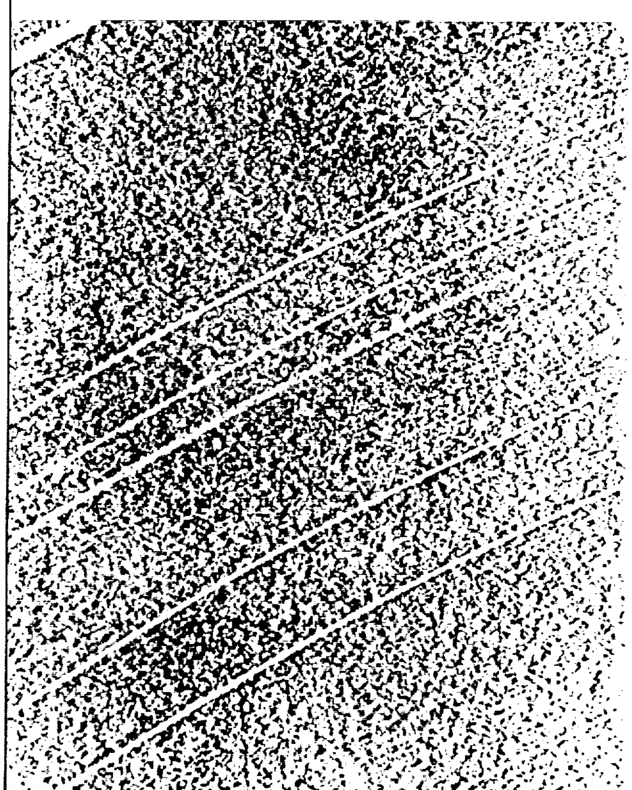
NEW OBJECTS DISCOVERED

- About 2,000 asteroids, including new classes (e.g., Atens)
- About 100 comets
- Radiation belts and magnetosphere of Jupiter
- Clouds on Titan
- Large particle clouds around comets
- Rings of Uranus
- Ring arcs of Neptune
- Io's sodium cloud and torus
- Charon (satellite of Pluto)
- Leda (satellite of Jupiter)
- Chiron (most distant asteroid)
- Janus and Epimetheus (satellites of Saturn)
- Circumstellar disks of debris

NEW PROPERTIES, CONSTITUENTS, AND PHENOMENA

Solar System

- Precise scale of the solar system (measurement of the astronomical unit)



Ground-based observations first detected the rings of distant Uranus, shown here in a Voyager 2 photograph.

Mercury

- 59-day rotation
- Sodium atmosphere

Venus

- 243-day nonresonant retrograde rotation
- 4-day upper atmospheric retrograde superrotation
- Surface temperature and pressure (greenhouse)
- Topography and continental landforms from radar
- Sulfuric acid in clouds
- Mesospheric laser emission in atmosphere
- Lower atmosphere composition: CO_2, CO, HCl, HF, H_2O, SO_2, NO
- Upper atmospheric composition: H,D

Moon

- Regolith roughness at microscales and smoothness at decimeter scales
- Pyroxene, olivine, plagioclase in lunar rocks
- Low-resolution geochemical maps showing stratigraphic heterogeneity and systematics

Mars

- Atmosphere: low pressure, CO_2 major constituent, minor constituents include H_2, CO, O_2, O_3
- Large-scale topography
- Surface dust layer
- Temperature-pressure structure of atmosphere
- Gravity waves in upper atmosphere
- Oxidized iron-bearing minerals in surface rocks

Jupiter

PLANET:

- Excess thermal radiation from interior
- Location and motions of cloud layers
- Global wind velocities
- Thermal structure
- Numerous atmospheric constituents, including H_2O, C_2H_6, C_2H_2, HCN, PH_3, CO, GeH_4, and compounds with deuterium and isotopic carbon
- Polar aurorae

SATELLITES:

- Sizes
- Water frost on Europa, Ganymede, Callisto
- Sulfur compounds on Io
- Io hot spots
- Anomalous radar properties of Europa, Ganymede, and Callisto
- Asteroid-like properties of outer satellites (colors)
- Surface variegation of Galilean satellites

Saturn

PLANET:

- Numerous atmospheric constituents, including H_2, gaseous hydrocarbons, PH_3, and compounds with deuterium and carbon isotopes

RINGS:

- Macroscopic particles
- Water ice
- Gross structure of A, B, C rings
- Material interior and exterior to A, B, C rings

SATELLITES:

- Cloud layer, "dense" pressure (greater than 0.1 bar) atmosphere on Titan
- Water ice surface composition of most satellites
- Dark organic material on Iapetus
- Hyperion's anomalous rotation properties
- Gaseous and solid hydrocarbons in Titan's atmosphere

Uranus

RINGS:

- Narrow width and structure
- Low-albedo particles in rings

SATELLITES:

- Water ice surface compositions of five largest
- Albedos of four largest
- Radii of four largest

Neptune

PLANET:

- Gaseous hydrocarbons in atmosphere
- Weather and atmospheric variability on several time scales
- Rotation period from photometry
- Correlation of atmospheric brightness with solar cycle
- Pressure temperature structure of upper stratosphere from occultations

SATELLITE:

- Hydrocarbons in spectrum of Triton
- Surface variegation of Triton
- Possible nitrogen on Triton's surface

Pluto

PLANET:

- Rotation period
- Surface variegation
- Secular change in brightness
- Hydrocarbon (methane) ice on surface
- Radius
- Mass
- Existence of an atmosphere

Jupiter's unusual moon, Io.

SATELLITE:

- Locked synchronous rotation-revolution
- Radius
- Water ice surface

Asteroids

- Clustering of orbital parameters into family groupings
- Sizes and rotations of hundreds
- Shape information (projections and averages), including probable double bodies
- Compositional gradational structure from 2 to 5 astronomical units
- A few masses
- Presence of meteoritic mineral assemblages, including basalt, pure olivine, and pure metal
- Presence of surface features
- Gross morphological/topographical characteristics for a few
- Compositional variety of near-Earth asteroids
- Probable connection of specific meteorite types with specific near-Earth asteroids
- Possible connection of certain dynamic types with extinct comets

Comets

- Numerous neutral/charged species in cometary atmospheres
- Low-albedo surfaces of some comet nuclei
- Some rotations
- Hot silicates in the dust fraction
- Low-albedo dust component

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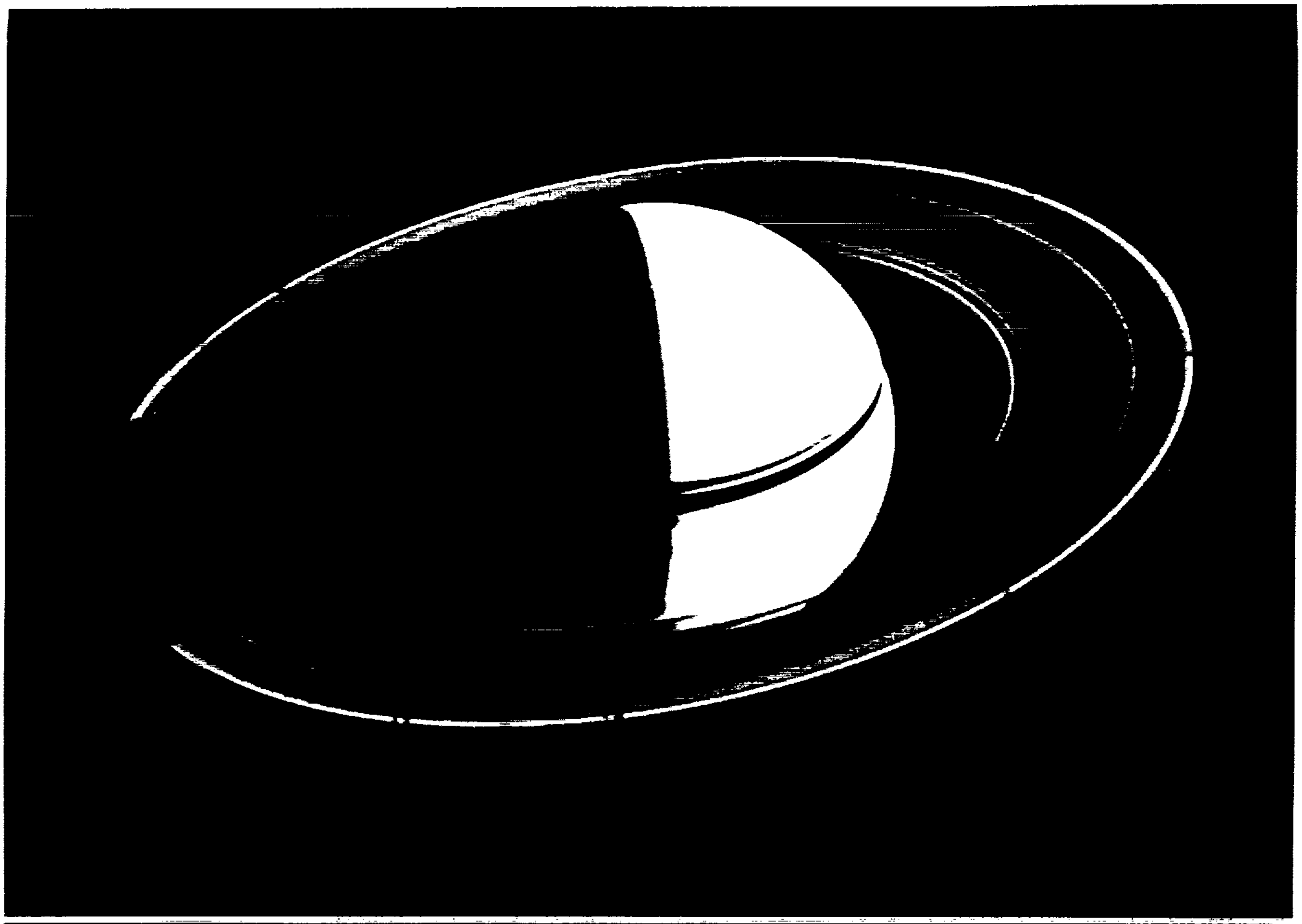
Four-and-a half days after its closest approach to Saturn, Voyager 2 looked back at the ringed planet.



Planetary Astronomy Goals, Objectives, and Opportunities

The last twenty-five years have brought remarkable progress toward understanding our solar system. More than two dozen spacecraft have made close encounters with most of the planets, from Mercury to Uranus, in addition to dozens of moons and three ring systems. Observations from Earth-based telescopes have added a unique perspective to that provided by planetary exploration missions, and these observations have extended the range of studies to numerous solar system objects—comets, asteroids, and satellites—not yet visited by U.S. spacecraft. The remote techniques of astronomy augment the *in-situ* measurements from spacecraft and help to establish a foundation of knowledge on which we can expect to build a much deeper understanding of our solar system and, indeed, of life itself.

Charter of the Planetary Astronomy Committee

In 1980, the Solar System Exploration Committee (SSEC) of the NASA Advisory Council undertook a review of U.S. planetary exploration to develop a program that would ensure that the United States can preserve its leading role in solar system exploration and that would allow the nation to capitalize on its 25-year investment in this enterprise. The SSEC was charged with developing a strategy for solar system exploration through the end of this century, based on the scientific priorities established by the Space Science Board of the National Academy of Sciences, and augmented where necessary to reflect evolving scientific priorities.

The SSEC recommended a Core Program and an Augmented Program for planetary exploration. The Core Program consists of two parts: an Ongoing Base Activities Program, including basic research, mission operations and data analysis, technology development, and advanced planning; and a Core Planetary Missions Program. Both elements would be sustained by an annual expenditure of only about four percent of the entire NASA research and development budget. More technically challenging missions of high scientific priority were identified by the SSEC as possible augmentations to this Core Program, if additional funding became available. The recommendations of the SSEC were summarized in two publications: "Planetary Exploration through Year 2000: A Core Program," published in 1983, and "Planetary Exploration through Year 2000: An Augmented Program," published in 1986.

In 1986, the NASA Administrator formed a task force, chaired by scientist and former astronaut Sally Ride, to identify long-range goals for the U.S. civilian space program. In the process of their deliberations, the task force developed four initiatives for exploration; one of these was a plan for solar system exploration. The Solar System Exploration Initiative combined elements of both the Core and Augmented Programs, and the task force recommended that these missions be enhanced and implemented at a faster pace than the constrained program envisioned by the SSEC. These recommendations were published in 1987 in "Leadership and America's Future in Space."

Although the SSEC and other NASA studies concentrated on planetary flight missions, these plans recommended or presupposed the existence of ongoing and healthy research and analysis programs, including the ***planetary astronomy program,*** which involves studying the solar system using ground-based, airborne, and Earth-orbital telescopes. Planetary astronomy plays many unique roles in supporting the nation's solar system exploration program, not only providing the necessary guidance to carry out a planetary spacecraft mission, but also allowing complementary and follow-up observations. Ground-based, airborne, and Earth-orbiting astronomy provide excellent testbeds for prototype hardware, offer quick response times for observing targets of opportunity such as Earth-approaching comets and asteroids, provide the capability for synoptic planetary observations, and make it possible to extend the knowledge of a few representative comets and asteroids to additional members of these populations. In addition, the planetary astronomy discipline provides excellent training opportunities for students, who will eventually use their skills and insights to support future planetary missions.

Several factors in today's environment suggest that the importance of planetary astronomy is likely to increase during the next several decades, and that this discipline should play a larger role in realizing the scientific goals established by the Space Science Board of the National Academy of Sciences and by the SSEC. Among these factors are:

• The capabilities of ground-based telescopes are rapidly improving, due to the availability of high-sensitivity array detectors, larger mirror diameters, and improved image quality.

• We are moving into the era of sophisticated, long-term Great Observatories in space, which include the *Hubble Space Telescope* and the *Space Infrared Telescope Facility*—instruments with great potential for planetary research.

• Instrumentation has now improved to the point where detection of other planetary systems is technologically feasible, thus creating an opportunity to place the study of our own planetary system in a broader galactic perspective.

• Future planetary spacecraft missions generally emphasize long-term orbital and rendezvous missions that are scientifically enhanced by concurrent observations from the ground and Earth orbit.

• Flight missions may increasingly emphasize the solar system's primitive bodies, which exist in such enormous, diverse populations that astronomical techniques are required to provide complementary data about a large sample of the general population of such objects.

• The educational role of planetary astronomy is highlighted by the fact that the high costs and long lead times associated with flight missions make it increasingly difficult to train new planetary scientists through flight missions.

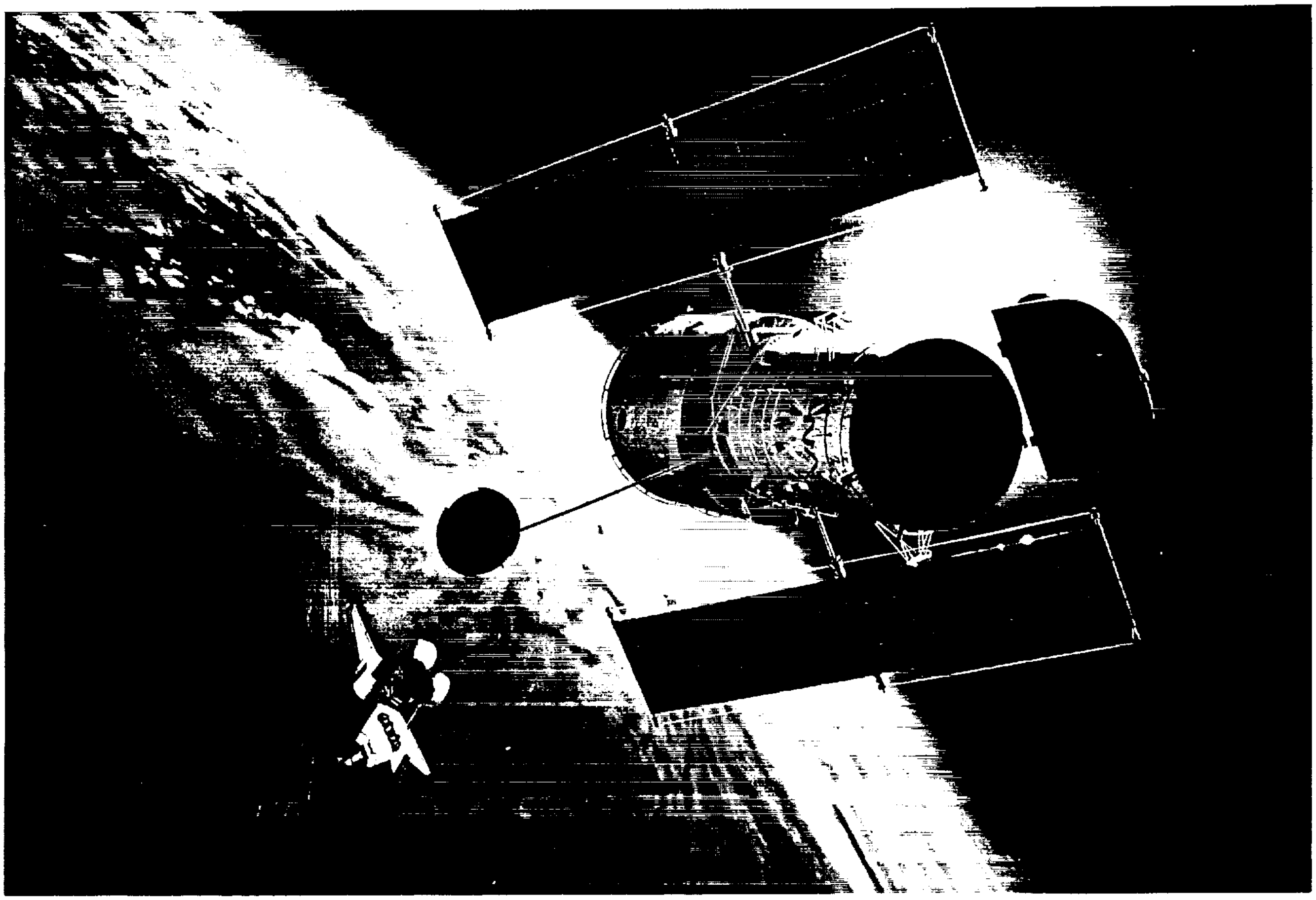
To take advantage of these factors, and to ensure and sustain a vigorous and viable program for planetary astronomy, the Director of the Solar System Exploration Division of NASA's Office of Space Science and Applications formed the NASA Planetary Astronomy Committee in December 1985. The purpose of the Committee was to advise the Division and its Solar System Exploration Management Council on the status and future of planetary astronomy. The Planetary Astronomy Committee was asked to recommend, consistent with the SSEC program approach, a strategy for planetary astronomy through the year 2000, and, in particular, to consider the continued characterization and detailed study of the solar system using ground-based, airborne, and Earth-orbital capabilities, and the initiation of the search for and characterization of other planetary systems.

The Committee examined the scientific rationale and opportunities for planetary exploration, reviewed the status and health of planetary astronomy, and developed recommendations for the NASA planetary astronomy program. This report describes the findings of the Committee and articulates its recommendations for ground-based, airborne, and Earth-orbital planetary astronomy.

Scientific Background

Planetary astronomy is one of the oldest scientific disciplines. Understanding and interpreting the motions of the planets was a

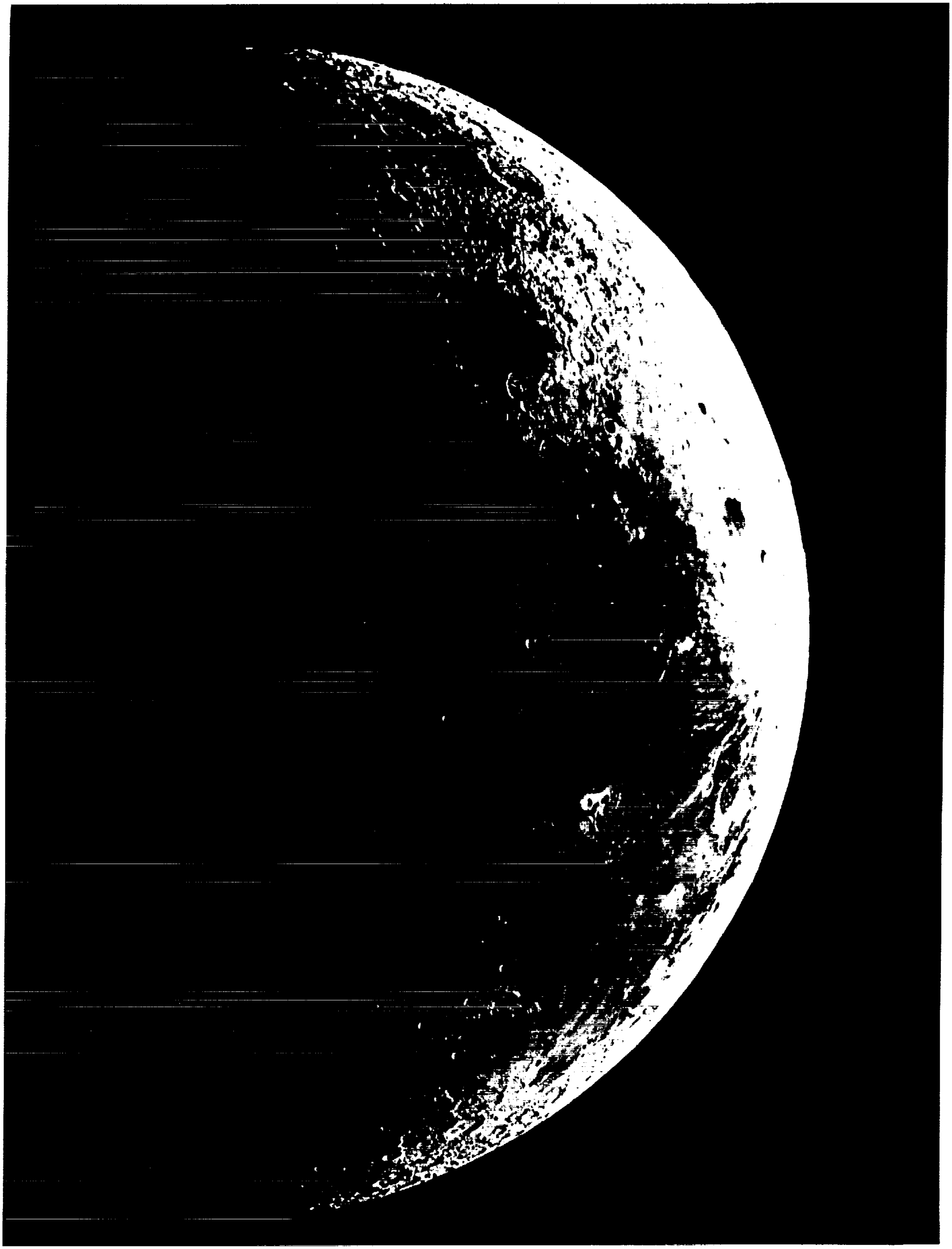
NASA's **Hubble Space Telescope** *will orbit above the distortions generated by Earth's atmosphere to open a new era in our understanding of the universe.*



matter of major concern to all early civilizations, in Mesopotamia, Egypt, Greece, China, and the Americas. In more recent centuries, the great pioneers of modern science—Copernicus, Brahe, Galileo, Kepler, and Newton—all devoted much of their energy to studying the nature and motions of the planets. As recently as the beginning of the nineteenth century, the conclusion could fairly be drawn that planetary studies dominated the entire field of astronomy. Planetary research led the way toward the modern scientific world view, with its emphasis on observation and experiment, on the mathematical formulation of scientific law, and on the universality of natural phenomena.

The first questions addressed by planetary astronomers were concerned primarily with celestial dynamics—understanding how the bodies of the solar system moved under their mutual gravitational attraction. But from the time that Galileo first looked at the Moon through his telescope, astronomers also began to investigate the nature of the other worlds in our solar system. The concept that Earth is a planet, and that the planets are other worlds, represented a profound advance in human understanding. For the past 150 years, planetary astronomers have focused on the physical and chemical properties of the planets. We have sought to understand their environments and the processes that shape them. Gradually, this approach has widened to include not only the major planets, but also

Our Moon, photographed in exquisite detail from an Earth-based observatory.



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the satellites, asteroids, comets, rings, and other elements of the solar system.

During the past 25 years the traditional discipline of planetary astronomy has become just one of several ways of studying the solar system. Meteoritics—the study of the celestial samples that fall from the sky—has emerged as one of the most important means of understanding the detailed chemical nature and history of some members of the solar system family, as well as of the earliest stages in the history of the solar system itself. With the advent of spacecraft missions, other disciplines of planetary science—planetary geology, planetary geophysics, planetary meteorology, and space physics—have also come to the fore. But the flowering of other approaches has in no way decreased the importance of planetary astronomy.

A substantial fraction of what we know about the solar system still comes from observations carried out with ground-based and orbiting optical telescopes, from high-flying airplanes, or with radio and radar telescopes. We continue to discover new objects and to deepen our insights concerning the objects and phenomena that are already well known to us. It was not until 1969 that we first learned of the excess heat radiated by the giant planets; observations a few years later first revealed that many satellites of the outer planets, as well as the rings of Saturn, are composed of water ice; the complex rings of Uranus were discovered only in 1977, and Pluto's moon, Charon, in 1978; and numerous discoveries during the same span of years have gradually revealed the chemical and isotopic compositions of planetary atmospheres and the comae of comets. In the last decade alone, a thousand asteroids and dozens of comets have been discovered and their orbits have been plotted. Space missions to the planets and the development of other disciplines of planetary science have only accelerated the pace of astronomical discovery and enhanced the significance of the data collected by our telescopes.

If the first goal of planetary science has been discovering the bodies of the solar system and understanding their motions, and the second goal has been investigating these objects as worlds, then the third major goal is developing a theory of the origin and evolution of the solar system. It is toward this end that much of the research in planetary astronomy is directed today. Many aspects of different theories of solar system origin can be tested by astronomical observation. In fact, many observations require the flexibility, unique to astronomical approaches, to observe a broad range of bodies, including the small and chemically primitive comets and asteroids. In addition, astronomical techniques have progressed to the stage where we can also begin the search for other planetary systems, circling other stars. The discovery of such systems would profoundly affect our ability to generalize from our own particular system to issues of planet formation and evolution throughout the Galaxy.

Later in this chapter, we develop at some length a strategy for the search for other planetary systems, as well as complementary investigation by astronomical observations of the contemporary formation of stars and (possibly) their accompanying planets. These areas are at the frontier of astronomical research today, and it is important that we pursue them. But it is equally important that we continue the fruitful study of our own planetary system. Only by combining these approaches—by studying our own system in detail while at the same time searching for evidence of other systems—can we hope to develop a general understanding of the origin and evolution of the planets, including our own planet, Earth.

Solar System Exploration Goals

The goals of the NASA Solar System Exploration Program are:

• **Origin and Evolution:** To determine the present nature of the solar system, its planets, and its primitive bodies, in order to understand how the solar system and its objects formed, evolved, and (in at least one case) produced environments that could sustain life.

• **Comparative Planetology:** To better understand the planet Earth by determining the general processes that govern all planetary development and by understanding why the "terrestrial" planets of the solar system are so different from each other.

• **Pathfinders to Space:** To establish the scientific and technical data base required for undertaking major human endeavors in space, including the survey of near-Earth resources, the characterization of planetary surfaces, and the search for life on other planets.

The Committee concluded that these goals, all of which are directly addressed by planetary astronomy, should be sustained, but that the scope of the first should be expanded to include scientific studies of other planetary systems and presolar nebulae. Through discussions that focused on the importance of understanding the general planetary formation process as an aid toward understanding our particular solar system, the Committee determined that the relevant expansion of this goal for solar system exploration includes:

• To determine the number and distribution of planetary systems in our galaxy, and to understand the physical processes that lead to these systems; in particular, to assess the uniqueness of the solar system.

Planetary Astronomy Objectives

The pursuit of a number of objectives is fundamental to understanding planetary systems. Those objectives that can be addressed by ***planetary astronomy*** include:

1. Discover and provide initial characterization of small bodies in the solar system as an aid toward understanding the early conditions that led to the solar system's formation and subsequent evolution.
2. Characterize planetary surfaces and environments, and measure the ongoing physical processes that shape them.
3. Measure the chemical and mineralogical compositions and isotopic abundances throughout the solar system.
4. Characterize the structure, composition, and dynamics of planetary atmospheres and climates.

5. Detect and characterize other planetary systems, protostellar disks, and circumstellar nebulae.

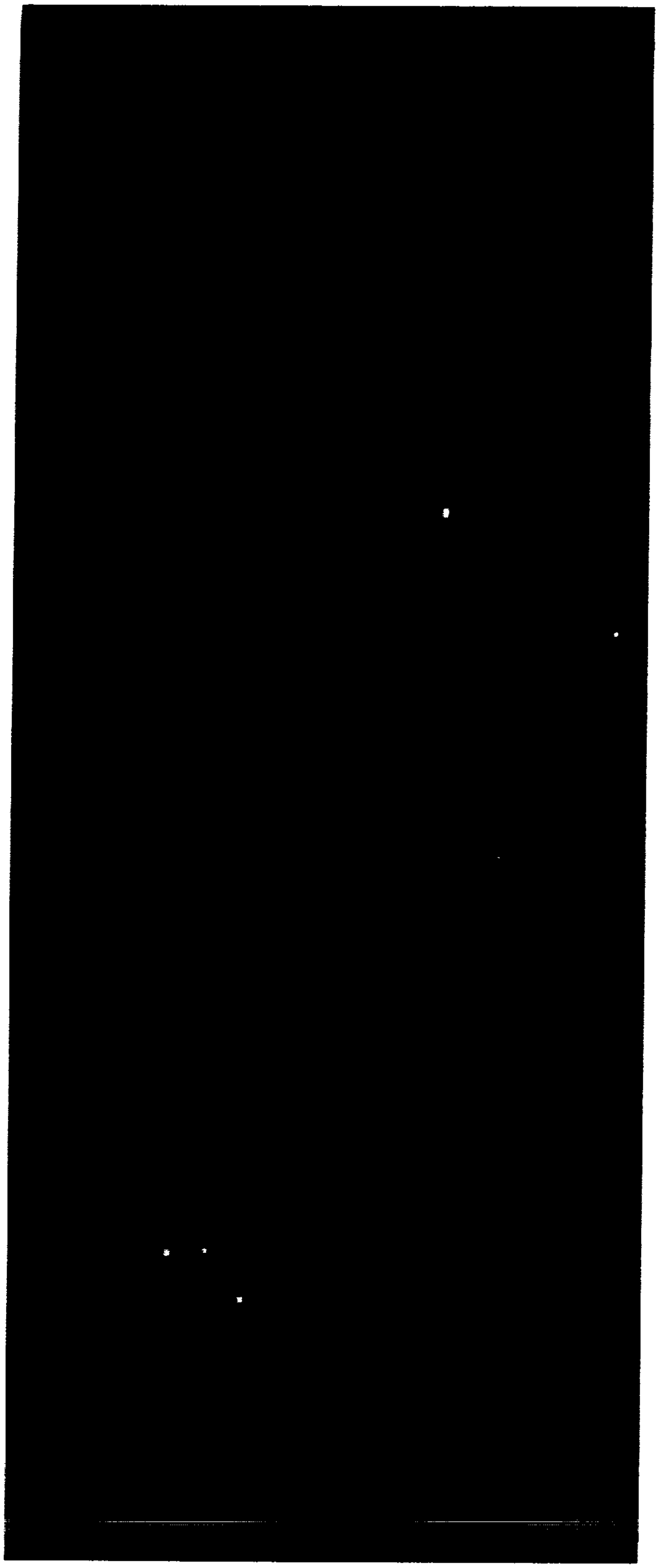
The first four objectives encompass the present activities of the planetary astronomy research and analysis program, and the pursuit of these objectives can be expected to continue and to expand in importance during the 1990s. The last objective represents expanded elements for the planetary astronomy program, to be pursued in collaboration with non-planetary astronomers who are interested in the origins of stars and planets.

Detection and Study of Other Planetary Systems: A New Initiative

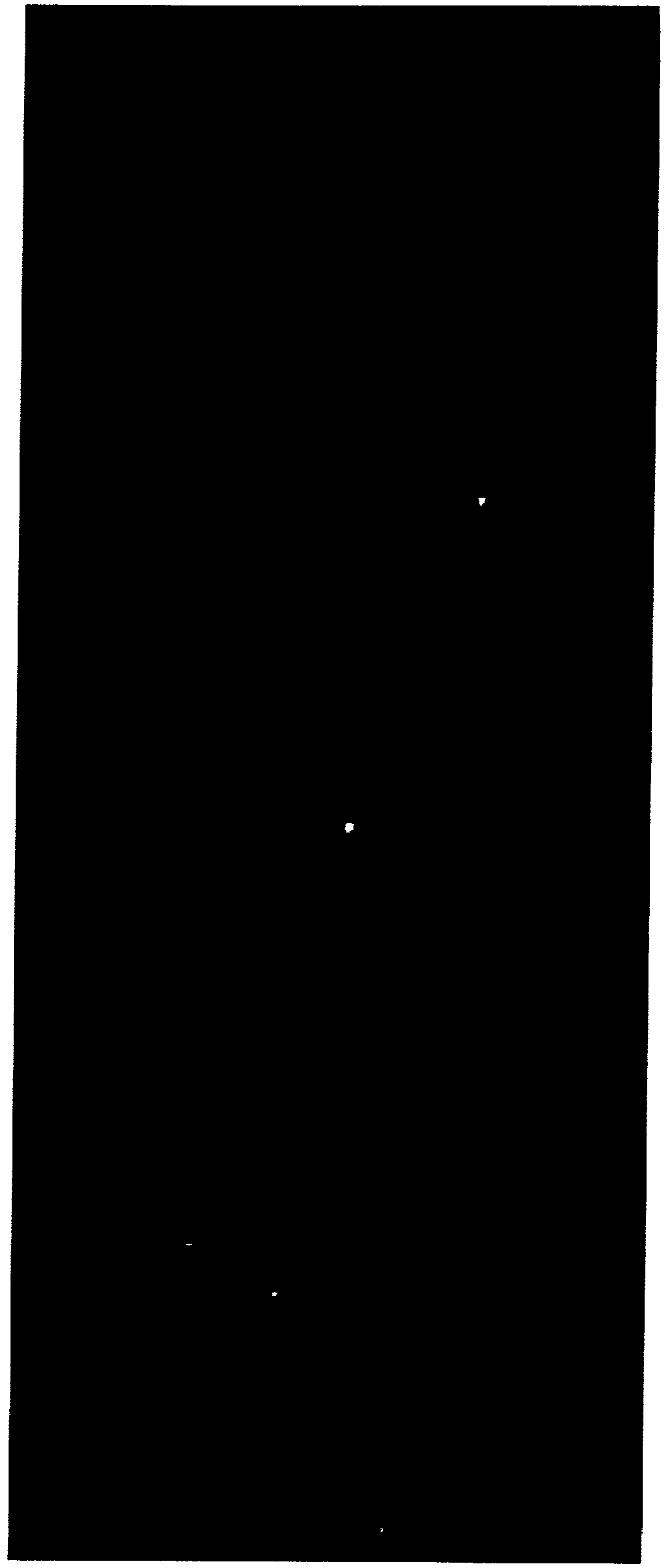
Detecting and characterizing other planetary systems, protostellar disks, and circumstellar nebulae offer the potential to expand our horizon from the Sun's immediate neighborhood to a much more general study of other planetary systems. New technologies that provide access to the near environments of stars have created this expanded frontier for planetary astronomy. Wider wavelength coverage, improved image quality, and increased measurement precision are now achievable, especially with instruments in space. For the first time, planetary system genesis can be studied directly in the context of star formation. In addition, stellar environments can be probed much more deeply for evidence of either planetary systems or alternative end states of the processes involved in planetary system formation. Such opportunities, as a class, will eventually create a new field of "comparative planetary system studies," which will be of great importance for our understanding of Earth and the other planets in our own system.

Many phenomena associated with other planetary systems are potentially accessible to astronomers. The nearest star is about 4 light-years away, and several hundred stars of diverse types are within 50 light-years. The nearest regions of active star formation, and perhaps of planet formation as well, are 10 times more distant. Modern ground-based telescopes at excellent sites such as the Mauna Kea Observatory in Hawaii routinely achieve a resolution of 1 arcsec (an angle equal to the apparent diameter of a 1-kilometer crater on the Moon). The *Hubble Space Telescope,* now scheduled to be launched in 1989 to observe the universe in visible and ultraviolet radiation, is expected to be 10 times as powerful, with a resolution of 0.1 arcsec. At a distance of 50 light-years, the *Hubble Space Telescope* can distinguish features with dimensions less than 2 astronomical units, which is the diameter of Earth's orbit: 300 million kilometers. In the star-forming regions 500 light-years away, the same telescope can resolve features down to 20 astronomical units, which is approximately the diameter of Saturn's orbit. Ground-based telescopes can resolve 20 astronomical units at 50 light-years, and 200 astronomical units at 500 light-years. In principle, then, we can "see" into other planetary systems using modern, high-performance telescopes.

Planets, forming or formed, are faint objects compared to stars, and through the telescope, stars cast a bright, unwanted glare that obscures the dim signals of circumstellar planetary material. In



Artist's conception of the formation of a star.
Here, a molecular cloud core forms within a cloud of debris.



The core undergoes gravitational collapse to form a protostar.

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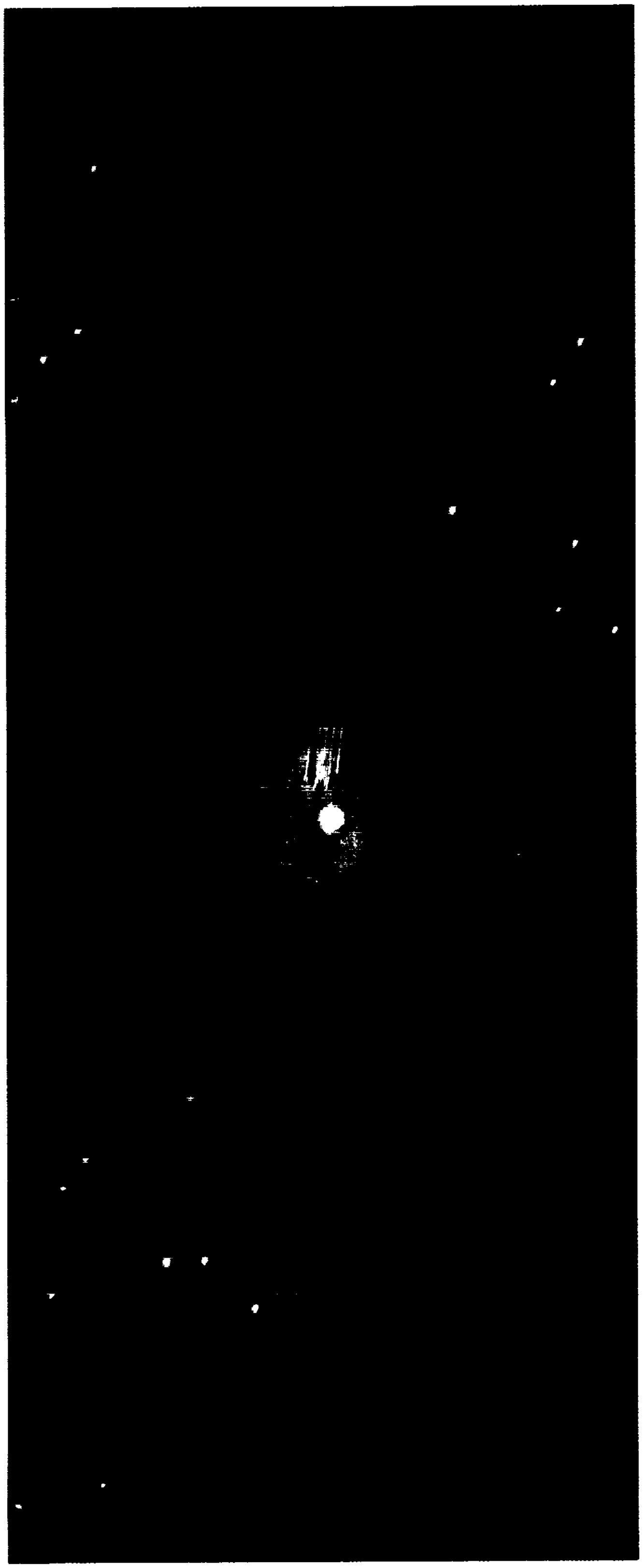
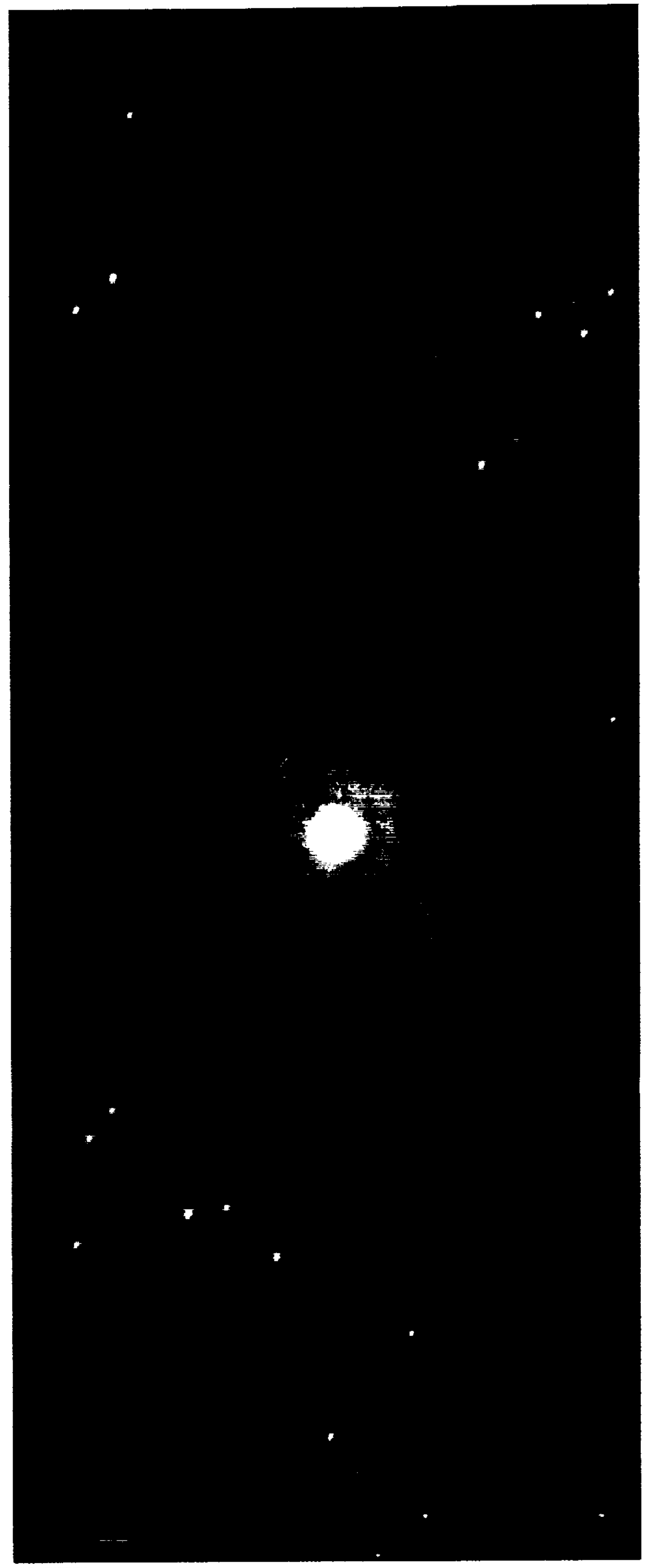


Infalling gas becomes the energy source for the protostar.



The star has entered the pre-main sequence phase.

addition, regions of star formation are embedded in dust-laden interstellar clouds that obscure the line of sight. Lifting or penetrating those observational impediments is a challenge that now is addressable by a variety of innovative technologies. First, infrared wavelengths offer less extinction by dust and a more favorable ratio of planetary versus stellar flux. Second, smoother and cleaner telescope optics, which are now within the state of the art, can better control scattered light and can provide more stable, sharper image profiles. Third, precision positional (astrometric) and velocity measurements can overcome the extreme difficulty of direct planetary detection by seeking evidence of other planetary systems indirectly through studies of the reflex motion of the central star responding to the gravitational forces of its major planets.

The Planetary Astronomy Committee has examined opportunities for pursuing the planetary science objectives of searching for other planetary systems. In recommending that this direction be pursued, the Committee emphasizes two important elements of programmatic strategy. The first element is the scientific importance and cost-effectiveness of achieving planetary astronomy's goals through existing projects of NASA's Astrophysics Division, particularly the Great Observatories. The second element is the requirement of an extensive program base with repeated measurements; a certain degree of risk is inherent in pursuing a narrow approach or a single technique. Particularly in the case of planet detection, we do not really know at the present time what the best approach is, or even whether a single approach will pay off—many have strengths; many have weaknesses. In any event, a detection by one technique must be examined and clarified by others.

Studies of Circumstellar Material

As a process, planetary system formation is thought to be embedded in the master process of star formation, for which current theories define an evolutionary path from interstellar clouds to the "main sequence" of normal, hydrogen-burning stars. The connection between the steps on this path and planetary science is contained in the evolution of the dust and gas that are gravitationally bound to the forming star; these clouds of debris are the potential environments and the ingredients for planet formation.

Star and planet formation begin together in a molecular cloud. Density enhancements, known as molecular cloud cores, form within the cloud. At some point, a core undergoes gravitational collapse, and it forms a protostar. These diffuse objects are characterized by very low effective temperatures, and they emit most of their light at infrared and submillimeter wavelengths. As the protostar collapses, it becomes denser and hotter, consequently becoming detectable at shorter infrared wavelengths.

Recently, radio astronomers have located candidate early protostars, and observers at telescopes such as the NASA Infrared Telescope Facility in Hawaii routinely study the dust clouds that enshroud more evolved bodies called young stellar objects. In a few years, the new generation of long-wavelength observatories in space planned by NASA's

Astrophysics Division will provide additional, more powerful capabilities. For example, the airborne 3-meter telescope of the Stratospheric Observatory for Infrared Astronomy (SOFIA) could provide complementary high spatial and spectral resolution. Meanwhile, we can expect the new generation of ground-based optical/infrared telescopes, with apertures of 8 to 10 meters, to achieve even greater spatial resolution in studies at the wavelengths that penetrate Earth's atmosphere. The first of these instruments, the 10-meter W.M. Keck telescope on Mauna Kea in Hawaii, will be operational in 1992.

As a protostar evolves, it may develop a circumstellar disk of gas and dust, which is an essential element of current models of solar system formation. Density enhancements within these disks permit protoplanetary accretion on reasonable timescales, while dissipation within a disk leads naturally to a system of coplanar, nearly circular orbits such as those that characterize our own planetary system. Although dust disks around young stellar objects have been studied for almost a decade, only recently, with the *Infrared Astronomical Satellite (IRAS)* survey, disks and rings of planetary debris were identified around mature main sequence stars such as Vega (Alpha Lyrae) and Beta Pictoris. These clouds of debris, which may be the first signal of the presence of planetesimals or even planet-size objects around the stars that they orbit, appear to be quite common. The Vega disk, the paradigm of the class, is comparable in size to the outer solar system and contains at least 0.01 Earth-mass of material. Such disks may be accompanied by individual planets, but such planets remain undetectable by current technology.

The search for other planetary systems is an important specialty that we discuss in the next section, but we consider here the planetary science measurement requirements for the disk structures themselves. Infrared studies of such objects permit investigation of their thermal balance and mineralogical composition. The *Space Infrared Telescope Facility* and SOFIA will support such studies, and the *Hubble Space Telescope* will provide new information about morphology and optical and ultraviolet reflectivity. However, ground-based experience observing Beta Pictoris and searching for new such structures has highlighted a significant limitation of all optical telescopes, even the best currently planned for space: ineffective management of astronomical light by the telescope optics.

The light from the planetary-scale environment of a star competes on the focal plane of a telescope with light that is diffracted by the shape and size of the entrance pupil, or is scattered by telescope mirror roughness or surficial dust. Even a "perfect" 2-meter class optical telescope with no extraneous scattering could not directly detect our solar system from a distance of 10 light-years. Airy diffraction on the wings of the solar image would dominate the signals of Jupiter and the zodiacal light by five orders of magnitude. Additional light from mirror roughness and dust compounds the problem. To improve specific access to the dim light produced by planetary materials near young stellar objects and evolved stars, we must understand and reduce all contributors to the wings of the telescope image. The *Circumstellar Imaging Telescope*, currently under study at the Jet Propulsion Laboratory, is such a concept. The design of this telescope is directed at suppressing the diffraction wings by apodizing the entrance pupil. To gain the benefit of that optical trick, the mirror must be extremely smooth, so that scattered light is minimized, and significant gains seem to be achievable through newly developed polishing techniques. Such a low-scattered-light telescope would have wide application in stellar and planetary studies.

Regarding the *Hubble Space Telescope*, the *Space Infrared Telescope Facility*, and SOFIA, the Planetary Astronomy Committee recommends that the Solar System Exploration Division support these initiatives of the Astrophysics Division of the Office of Space Science and Applications by encouraging the potential application of these facilities to all areas of planetary science, including the observation of extra-solar planetary material. We also encourage the theoretical and laboratory studies needed to support the observational initiatives outlined in this section. Obtaining data is only one of three essential processes in the scientific research cycle; the other two are the analysis and the interpretation of the data. The ultimate scientific payoff comes from interpreting the analyzed data using theoretical models that embody scientific understanding by responding to new information and making new predictions.

Searches for Other Planetary Systems

Our interest in other planetary systems relates, in the first instance, to their origins. Current theories of star formation indicate that objects less massive than 20 Jupiters, or 0.02 solar masses, cannot form in isolation from the collapse and fragmentation of interstellar clouds, but require a different process, such as accumulation in a disk around a protostar. Because the discovery of such an object—sometimes called a brown dwarf or a super-Jupiter—would prompt immediate speculation on its "planetary" origins, we adopt the mass range up to 0.02 solar masses as one dimension of this discovery space for other planetary systems. We take another dimension of this discovery space to be the size of the planet orbit measured by the semimajor axis.

Direct imaging of other planetary systems is an exceedingly difficult proposition. The *Hubble Space Telescope* is the finest optical system ever developed for astronomy; however, as discussed earlier, our solar system viewed from a distance of 10 light-years would be impossibly swamped in the extended instrumental image of the Sun. Only a special telescope with low-light-scattering optics might be capable of detecting bodies the size of Jupiter around the nearest stars by direct imaging in visible light.

Massive planetary objects radiate their internal heat of formation at infrared wavelengths. The *Space Infrared Telescope Facility* could detect Jupiter-mass objects at the distance of the nearest stars, and it could detect planets in the range of 5 to 10 times the mass of Jupiter out to 30 light-years or more with a signal-to-noise ratio greater than 5.

The discovery of a single extrasolar planet would be a noteworthy event, but the major scientific benefit of searches for other planetary systems will come from systematic studies that will yield information on the statistical occurrence of planetary systems (e.g., their distribution as a function of spectral type of their central star) along with knowledge of the properties, such as size and orbital orientation, of the bodies of any planetary systems that are discovered. In the foreseeable future, such inventories must be based on the two indirect techniques that sense the stellar reflex motion: astrometry and doppler spectroscopy.

A star with a single planetary companion executes a reflex orbit that is a much smaller replica, in its projection on the sky, of the orbit of the planet itself. The dimensions of this stellar orbit are scaled down by the ratio of the planet to stellar mass. For a multiple planet system, the reflex motions of the star are independent and additive. The two measurable aspects of that stellar reflex orbit are the apparent displacement of the star, which can be sensed by precision astrometry, and the variation in its radial velocity, which can be detected by high-resolution doppler spectroscopy. These techniques are complementary, and both are maturing instrumentally to the point that their expected sensitivities in searches for other planetary systems are limited only by systematic effects associated with the physical properties of the stars themselves. (The technique of doppler spectroscopy may already have reached this mature state.) To achieve their full promise, precision astrometric searches for other planetary systems will have to be carried out from Earth orbit, above the distortions generated by Earth's atmosphere.

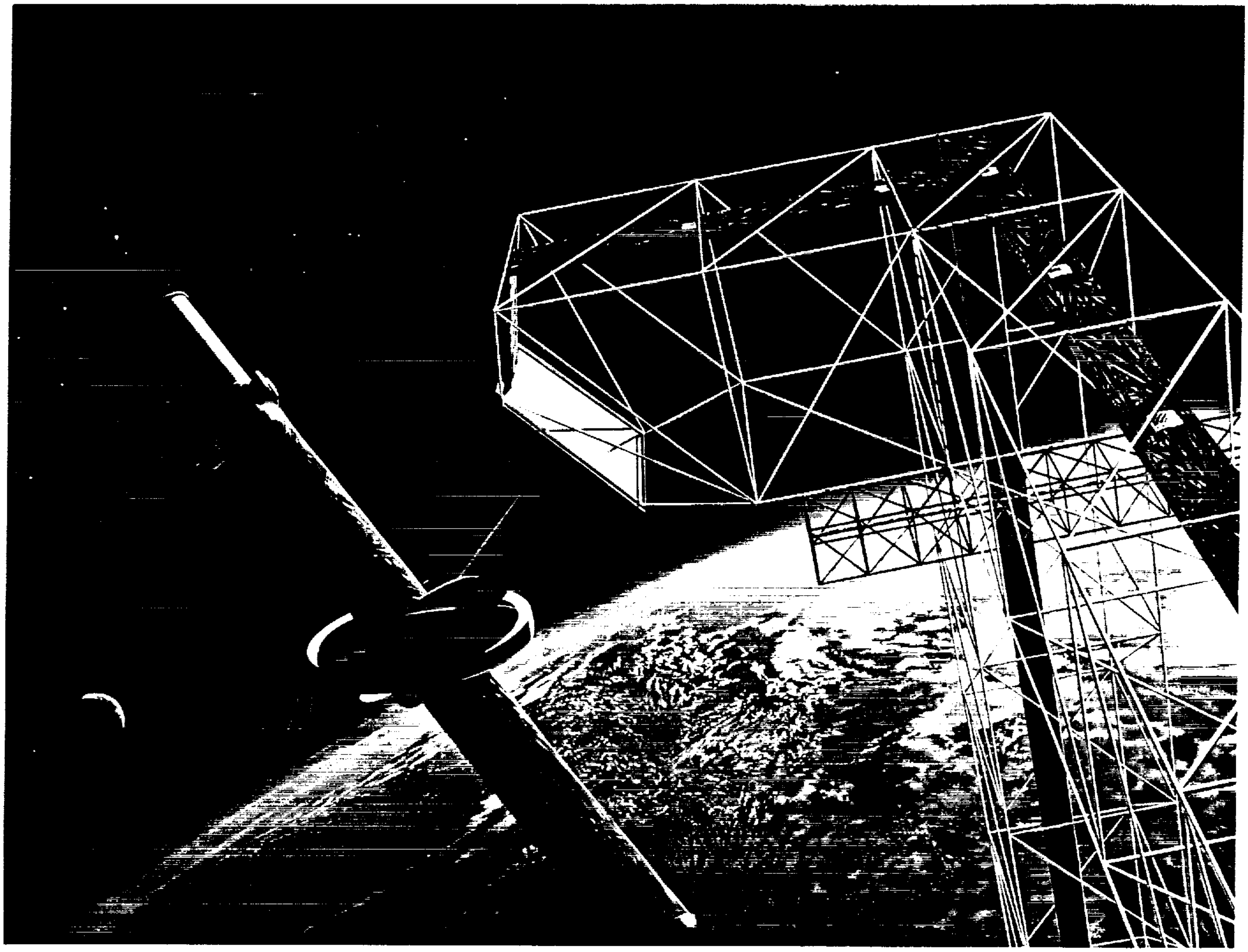
The doppler spectroscopy technique measures the radial (line-of-sight) component of the star's reflex motion to a precision of a few meters per second, using specialized spectroscopic instruments on large ground-based telescopes. This technique works most sensitively for low-mass stars, and it is especially sensitive to planets in smaller orbits.

Doppler spectrographic surveys are under way at the University of Arizona and at the Canada-France-Hawaii telescope at Mauna Kea, where precisions of 10 meters per second have been achieved over several years. The current state of the art would permit the detection of Jupiter around the Sun at the 1-sigma level, and of a Jovian planet in a smaller orbit around a star of 0.3 solar masses with much better confidence. The observers at Mauna Kea have accumulated a data base on about 20 nearby dwarf stars, and several observed candidates show marginal but still unconvincing evidence that "something" may be in orbit.

The primary advantages of the doppler spectroscopic technique are: (1) it can be implemented from the ground, and is, therefore, much less expensive than space-based systems, and (2) its power is explicitly independent of the distance of the star under study. (However, an implicit dependence arises from the need for the star to be bright enough to be studied with an adequate signal-to-noise ratio.) In addition, doppler spectroscopy is in many ways complementary to astrometric searches, which are most sensitive to planets in larger orbits. The complementary nature and the cost-effectiveness of doppler spectroscopy programs commend them as an important part of the overall effort to inventory stellar environments for planets.

An alternative approach to searching for other planetary systems is astrometry, in which the reflex orbit of the star is determined from precision measurements of its apparent position on the sky. Unlike doppler spectroscopy, the detection capability of astrometry is inversely proportional to distance. However, for nearby stars,

The Astrometric Telescope Facility,
shown here attached to Space Station Freedom, *is one instrument being studied for conducting the search for other planetary systems.*



astrometric precisions of 10 microarcsec (10 millionths of an arcsec) should be achievable from Earth orbit, and this level of precision is sufficient to detect planets with masses comparable to that of Uranus, in orbits with radii comparable to that of Jupiter. In space, either direct-imaging telescopes or interferometer systems can be designed to achieve the required level of precision.

A 1-sigma measurement accuracy of 10 microarcsec is the design specification of the *Astrometric Telescope Facility* currently under study at NASA. The facility, which is the best-studied example of a space-based, direct-imaging astrometric telescope, could provide detailed information about a discovered planetary system. The superposition of reflex effects from multiple planets could, in principle, be decomposed into its constituent parts, and the approximate eccentricities and inclination of the individual planetary orbits could be determined. While this space-based astrometric instrument is under development, near-term scientific and engineering merit could be gained from the earlier implementation, at a superb ground-based site, of a prototype of the detector assembly being considered for the space-based facility.

Such a ground-based telescope could discover planets the size of Jupiter or Saturn, but it cannot probe to the level of objects the mass of Uranus or Neptune, even for nearby stars.

An additional method has been proposed to search for planets orbiting other stars. This method is based on photometric monitoring programs that could detect the slight drop in the brightness of a star when a planet transits the stellar disk. Although such a technique could work, in principle, for the case of large planets in systems seen edge-on, the Committee judges this technique to be impractical. Even if a positive detection were made, questions would remain concerning confusion with starspots or other phenomena in stellar atmospheres, and an event could not be followed up on in order to characterize the newly discovered planetary system.

No discussion of planet searches is complete without stressing the commitment required to sustain them over the many decades of observation that are necessary to perform such a search. The longer the search, the "deeper" it is, and it is axiomatic that to be confirmed, a planet must be tracked over a considerable fraction of its orbit, no matter which technique is employed in its study. Long-term programs challenge funding agencies and observatories. The Planetary Astronomy Committee recommends that all parties to these important research programs—scientists, managers, and the public—be aware of the required commitments and foster an environment that can sustain them.

Summary

Planetary astronomy is an important, productive scientific discipline. Ground-based, airborne, and Earth-orbiting telescopes provide essential guidance and follow-up observations that complement the nation's program for spacecraft exploration of the solar system. The traditional goals of planetary astronomy—to discover solar system objects, to characterize planetary surfaces and environments and measure the physical processes that shape them, to measure compositions and isotopic abundances throughout the solar system, and to characterize planetary atmospheres and climates—remain the foundation of the program. Much of this report is devoted to describing new opportunities for these studies of our own planetary system. But new technology and upcoming Earth-orbital missions have broadened the horizons of planetary astronomy. We are on the threshold of having the capability to detect and characterize extrasolar planets, protostellar disks, and circumstellar nebulae. This information, combined with what we have already learned about our solar system, promises to bring a new perspective for understanding our solar system and its origin and evolution.

In the pages that follow, we describe the current status of the planetary astronomy program, and we discuss plans, challenges, opportunities, and recommendations for the future, directed toward a deeper understanding of our own solar system, and addressing the objective of discovering and characterizing other planetary systems as well.

Discovery Space for Astrometric and Doppler Spectroscopic Searches

Figures 1 and 2 show a discovery space for astrometric and doppler spectroscopic methods of searching for other planetary systems. The planets of our solar system are plotted on a grid of planetary mass, M_p, in units of M_{Sun} and semimajor axis, a, in astronomical units. The linear contours give the interpretation in terms of a and M_p of a 3-sigma detection at the projected accuracies of the two techniques. The contours are labeled by independently determined quantities: the stellar mass and the orbital period, where the first can be determined from the star's spectral classification and the second from tracking in time the displacement or velocity variation over a significant fraction of a cycle. The 0.3 M_{Sun} stellar mass contour is emboldened because that is a typical mass for nearby stars, which are largely red dwarfs. The domain to the left of the 3-sigma detection contours, for 0.3 M_{Sun} specifically, is labelled "undetectable."

For a given stellar mass, the a-M_p contour corresponding to a given reflex amplitude has a*M_p equal to a constant. According to Figure 1, a 3-sigma amplitude with a 1-year period for a 0.3 M_{Sun} star at 30 light-years distance would imply a planetary mass just greater than 10^{-4} M_{Sun} with an orbit the size of Venus's. Uranus around the Sun at 30 light-years would produce an 8-sigma or 80 microarcsec amplitude. For astrometry, the 1-sigma measurement accuracy of 10^{-5} arcsec is the design specification of the *Astrometric Telescope Facility* currently under study at NASA for deployment on Space Station *Freedom*.

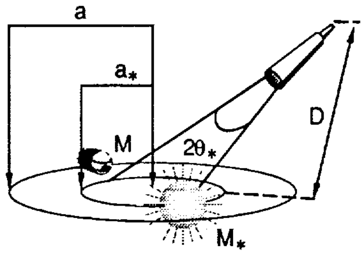
At a distance of 30 light-years, 10 microarcsec corresponds to about 1 percent of a solar diameter. Differential obscurations of a stellar disk—by starspots, for example—are not likely, on the basis of current models of sunspots, to displace the centroid of light by more than a few percent of that amount and so do not represent a lien against achieving better astrometric accuracy until accuracies of better than 10^{-6} arcsec are approached.

An astrometric telescope in space with 10^{-5} arcsec accuracy could provide rather detailed physical information about a discovered planetary system. The superposition of reflex effects from multiple planets could, in principle, be decomposed into its constituent parts. From the secular motion along the reflex orbit, the orientation of the orbit plane could be determined, and in particular, the difference between an actual ellipse and a projected circular orbit could be distinguished. These data on the alignment and eccentricity of planetary orbits are crucial to interpreting their genesis.

The doppler spectroscopic searches cover a somewhat different portion of discovery space than astrometric searches; in particular, they are more sensitive to discovery of planets in smaller orbits than those in larger orbits. The search capability of doppler spectroscopy is explicitly independent of the distance of a star under study. However, an implicit dependence arises from a need to have an adequate number of photons to do accurate spectroscopy. The 1-sigma measurement accuracy currently being achieved at ground-based observatories is 10 meters per second. Using very high spectral resolving power, atomic absorption lines formed in the atmosphere of a bright star can be located in wavelength to the required one part in 30 million, provided systematic error sources are very carefully controlled. This remarkable accuracy is just 2 percent of the Earth's equatorial rotation speed, and it may be comparable to convective vertical velocities in certain types of stellar atmospheres. Programs at a number of ground-based sites are currently under way, and they are proving the attainability of the 10 meters per second accuracy level.

The observed reflex speed varies as the sine of the angle between the line of sight and the pole of the planet orbit. As this angle is generally unknown for a given star, the expectation value of this quantity for randomly oriented orbits, 0.79, is adopted in Figure 2. For a given stellar mass, the contour on the a-M_p plane corresponding to a given projected reflex speed has a^2/M_p equal to a constant. According to Figure 2, a 3-sigma amplitude with a period of 10 years would imply a mass somewhat more than 10^{-3} M_{Sun} on an orbit about 3 astronomical units in size. Jupiter around the Sun would give a 1-sigma signal.

Figure 1



ASTROMETRIC PLANET SEARCH

$aM = a_* M_*$	*Physics*
$\theta_* = \frac{a_*}{D}$	*Geometry*
$M_\odot = 1, a_\oplus = 1, D_{1pc} = 1, \theta_{1''} = 1$	*Normalization*
$\Delta\theta_{1\sigma} \approx 10^{-3}$ arcsec	*Current Ground-Based*
$\Delta\theta_{1\sigma} \approx 10^{-5}$ arcsec	*Astrometric Telescope Facility*

Minimum Detectable Planetary Mass — M(3σ)

$$M = M_* D \theta_* a^{-1}$$

- M_* is determined from star's spectral class
- D is determined from star's annual parallax
- Assume D=10pc, then ~100 candidate stars

The interpretation of a 3-σ detection:

$$M(3\sigma) = \begin{Bmatrix} 3\times10^{-2} & \text{GB} \\ 3\times10^{-4} & \text{ATF} \end{Bmatrix} M_* a^{-1}$$

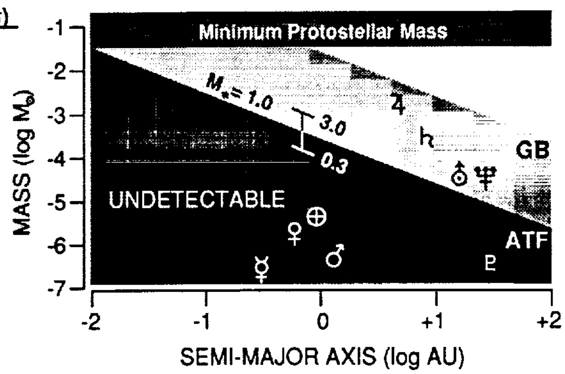
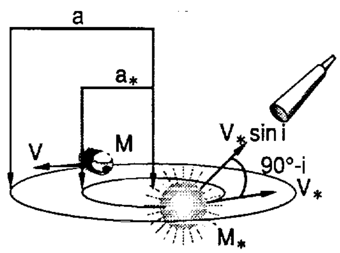


Figure 2



RADIAL VELOCITY PLANET SEARCH

$aM = a_* M_*$ $\frac{MV^2}{a} = \frac{GMM_*}{a^2}$	*Physics*
$M_\odot = 1, a_\oplus = 1, V_\oplus = 29.8\ \mathrm{km\,s^{-1}}$	*Normalization*
$\Delta(V_* \sin i)_{1\sigma} \approx 10\ \mathrm{m\,s^{-1}}$	*Current Ground-Based*

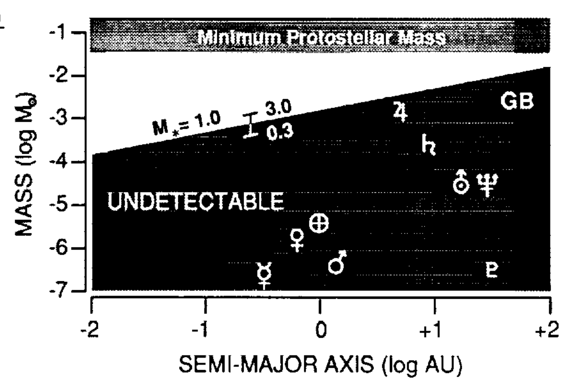
Minimum Detectable Planetary Mass — M(3σ)

$$M = v_\oplus^{-1} M_*^{\frac{1}{2}} V_* a^{\frac{1}{2}}$$

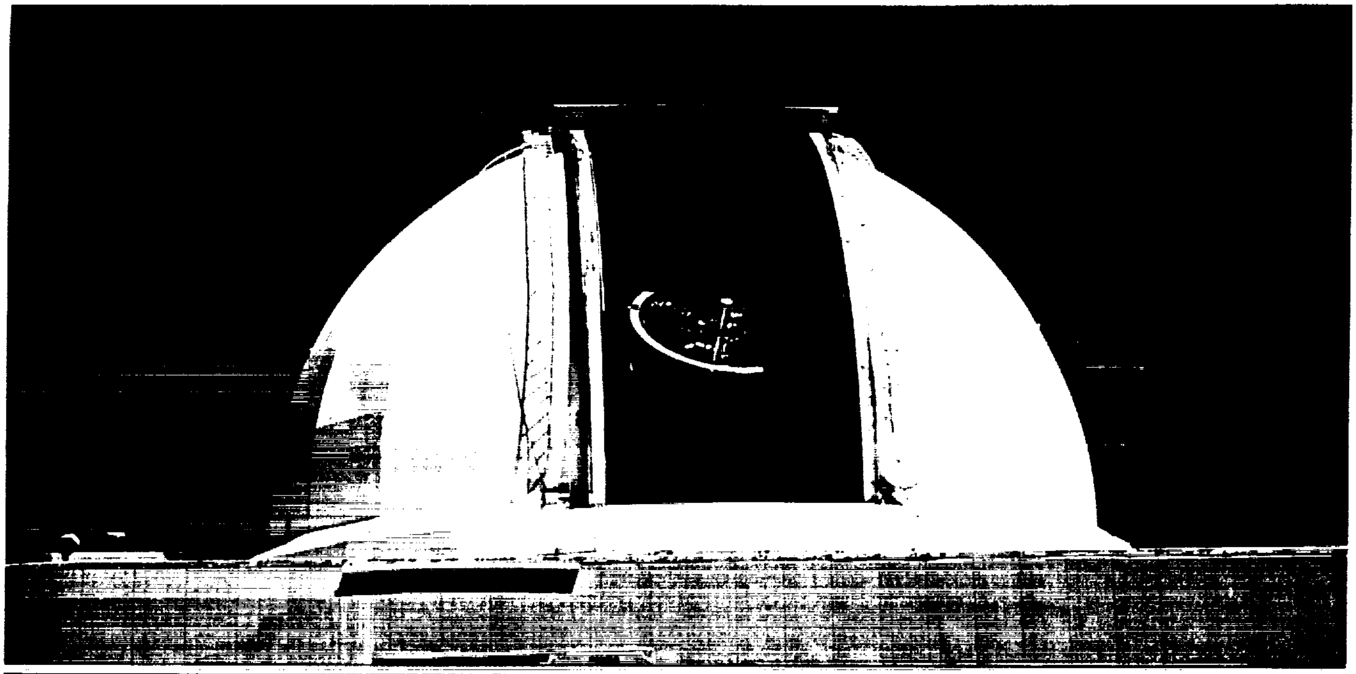
- M_* is determined from star's spectral class
- For randomized i, $\overline{\sin i} = 0.79$
  -observed amplitude is ~0.79 V_*

Then the interpretation of a 3-σ detection:

$$M(3\sigma) = \left[\frac{30}{0.79 \times 29.8 \times 10^3} = 1.3\times10^{-3}\right] M_*^{\frac{1}{2}} a^{\frac{1}{2}}$$



The Infrared Telescope Facility on Mauna Kea was established by NASA in the 1970s.



Planetary Astronomy Program in 1988: Status and Health

Planetary astronomy—the study of the planets, satellites, comets, asteroids, and other bodies of the solar system by astronomical methods—has contributed greatly to our current understanding of the solar system. Even in the Space Age, such remote studies continue to provide a steady stream of new discoveries that complement and enhance results from spacecraft missions to the planets. These astronomical studies, like the research on meteorites and lunar samples carried forward in laboratories around the world, constitute an essential element of our quest to understand the solar system and its origin.

During the first half of the 20th Century, planetary astronomy in the United States declined to the level of a minor branch of astronomical research, but a strong resurgence in this field began in the early 1960s as NASA initiated its program of lunar and planetary exploration by spacecraft. Not only did the need exist to learn as much as possible about the potential targets of spacecraft missions, but new goals also rekindled scientific interest in the planets. NASA, with its charter to explore the planets, was the natural agency to stimulate and support planetary astronomy. Accordingly, NASA established a grants program, supported graduate and postdoctoral students in planetary astronomy, and funded the construction of three large telescopes for planetary work at the Universities of Arizona, Texas, and Hawaii. These early NASA activities evolved into a formal research and analysis program called the NASA Planetary Astronomy Program, funded for the past two decades at a level of approximately $10 million per year (in FY88 dollars). In the 1970s, NASA established a 3-meter National Infrared Telescope Facility in

Hawaii, and contributed to the development and operation of the Arecibo planetary radar facility in Puerto Rico.

In view of these NASA initiatives, the National Science Foundation (NSF), which is the lead agency for general astronomical support in the U.S., was never called on to revise its distribution of funding to reflect the resurgent interest in the solar system. The level of NSF support for planetary astronomy has been constant at about 10 percent of the NASA level. From the 1960s to the present, NASA has remained the focus for ground-based as well as airborne and Earth-orbital planetary astronomy.

Planetary Astronomy Support in the United States

Within NASA's Solar System Exploration Division of the Office of Space Science and Applications, the Planetary Astronomy Program is on a level with several other research and analysis programs, which deal with planetary atmospheres, planetary materials and geochemistry (lunar samples and meteorites), and planetary geology and geophysics. The Planetary Astronomy Program funds the majority of Earth-based planetary remote-sensing data acquisition and interpretation in the United States. In addition, some planetary astronomy research is supported by other elements of NASA, including balloon and airborne astronomy, which are funded and managed by the Astrophysics Division, regardless of the nature of the objects of observation. Well over $1 million of planetary astronomy research each year is estimated to be supported by the Astrophysics Division.

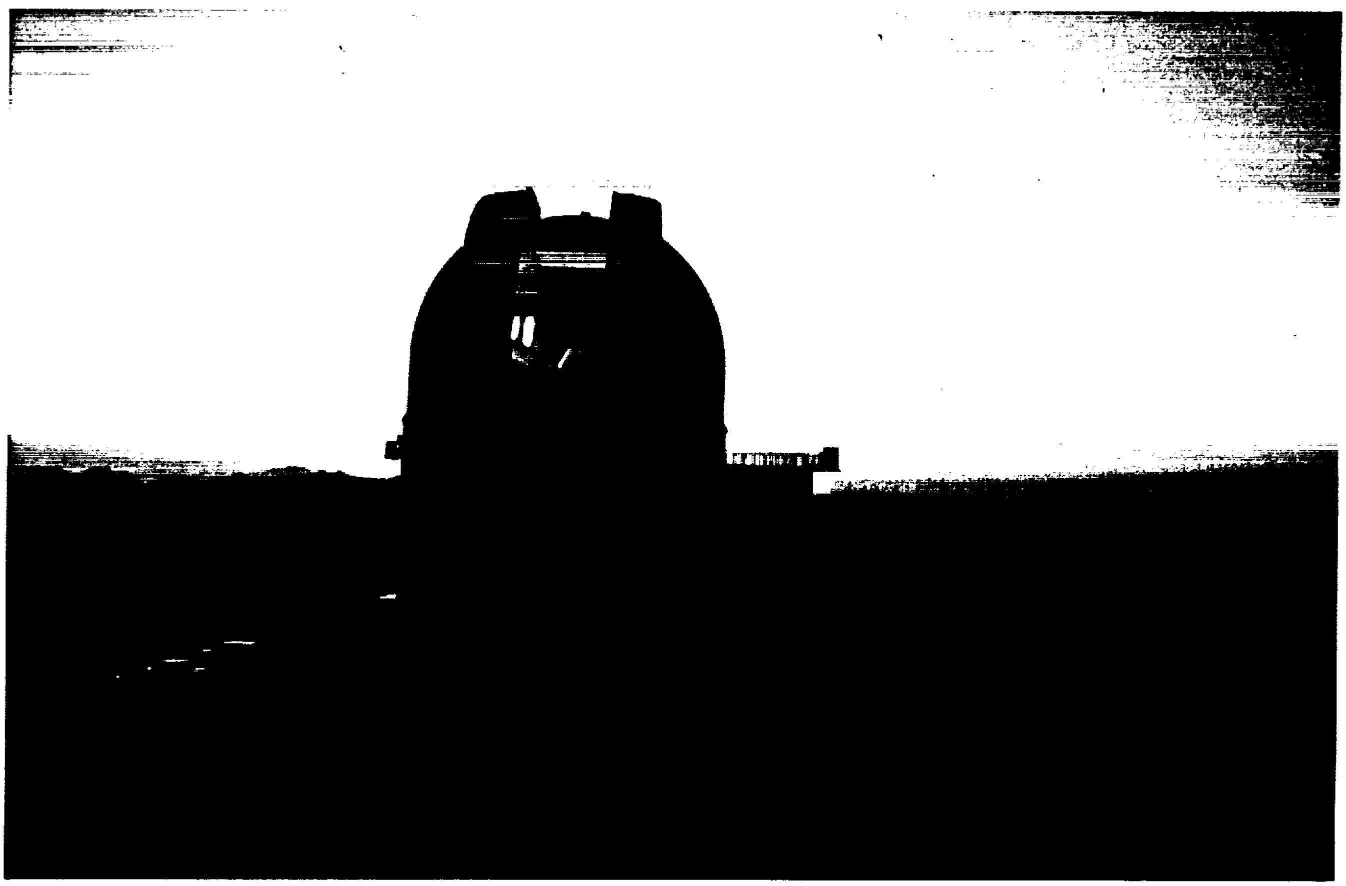
Earth-orbiting observatories funded by the Astrophysics Division also occasionally acquire planetary data. Recent examples include the *International Ultraviolet Explorer (IUE)* and the *Infrared Astronomical Satellite (IRAS)*; these programs have supported observations, data reduction, and data archiving, but they do not always support interpretive research. In the future, the Space Telescope Science Institute expects to support planetary observations on the *Hubble Space Telescope,* although neither the percentage of planetary observations nor the breadth of associated research activities is yet known.

Other Federal agencies fund some planetary astronomy research. The NSF planetary astronomy grants program has an annual budget of slightly more than $1 million, providing an alternative to NASA as a source of funding for a few planetary astronomers. Another part of the NSF Astronomy Division supports the development and operation of observatories (including support of some staff astronomers) used in part for planetary research, notably the National Optical Astronomy Observatories (which include Kitt Peak and Cerro Tololo), the National Radio Astronomy Observatory, and the National Astronomy and Ionosphere Center (Arecibo). Generally, however, only a small percentage of the effort at these facilities is devoted to planetary research, and this percentage has declined over the past decade. For example, the National Optical Astronomy Observatories program has reduced its planetary astronomy staffing levels to nearly the vanishing point, and during 1980 to 1983, only 2.6 percent of National Optical

Astronomy Observatories telescope time was scheduled for planetary observations. The fact that few requests are made to use these facilities for planetary observing both reflects and reinforces the widespread impression that planetary astronomers are finding it difficult to obtain observing time at NSF-supported national facilities.

Additional funds for planetary astronomy come from a wide variety of sources besides the Federal government, including state governments, private universities, and foundations. A number of observatories available for planetary use are operated by such organizations. With the exception of the Lowell Observatory and a few smaller organizations, less than 5 percent of the telescope time is estimated to be devoted to planetary work. Some state universities support planetary faculty, students, and observatory operations. However, relatively few planetary astronomers hold regular faculty positions, and all non-NASA support of planetary astronomy amounts to much less than the $8 to 10 million expended annually by the Solar System Exploration Division.

The Planetary Astronomy Committee estimates that approximately 200 planetary astronomers are active in the United States; this figure includes individuals who pursue astronomy on only a part-time basis.



The McDonald Observatory at the University of Texas, shown here at dusk.

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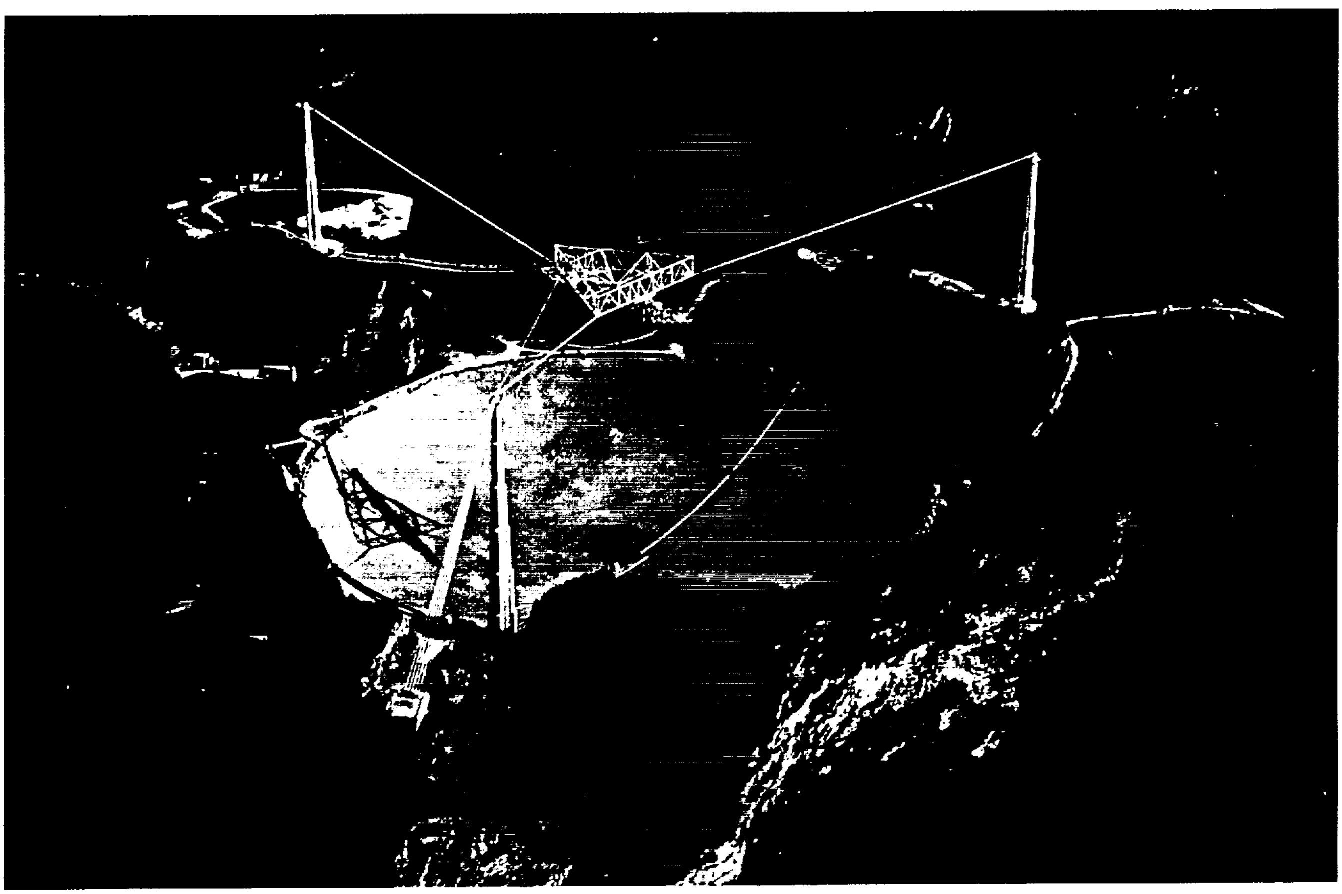
About 100 are principal investigators in the NASA Planetary Astronomy Program. During the 1980s, an average of between 5 and 10 students have been granted Ph.D. degrees in this field each year, which represents a significant drop from the 1970s. Thus, we estimate that planetary astronomers now constitute somewhat less than 10 percent of U.S. astronomers, and somewhat more than 25 percent of U.S. planetary scientists, most of the rest of whom have backgrounds in the Earth sciences.

Approximately half of the 200 U.S. planetary astronomers are optical/infrared observers. The Committee estimates that they are granted about 600 nights, or 6,000 hours, per year on U.S. telescopes of 2-meter aperture or larger: 50 percent on the NASA 3-meter Infrared Telescope Facility; between 10 and 30 percent each on the Hawaii 2.2-meter telescope and the Texas 2.7-meter and 2.1-meter telescopes; and less than 5 percent on each of the other telescopes of 2.0-meter or larger aperture. A comparable amount of time on smaller optical telescopes is also used for planetary observing. Other planetary observers use the Kuiper Airborne Observatory, space-based ultraviolet and infrared telescopes, or radio and radar telescopes.



The Arecibo Observatory in Puerto Rico houses a radar telescope, pictured here, that is the largest single-bowl type of instrument in operation.

The NASA Planetary Astronomy Program

This NASA research and analysis program is about two decades old. The current program can be summarized as follows:

• The annual budget of about $8.3 million (in fiscal year 1988) has been allocated by a combination of scientific peer review and programmatic decisions. Two to three percent of the funding is retained for NASA Headquarters management of the program. In the past, scientific peer review was accomplished by mail reviews and evaluated by the Program Manager, but in 1987 a shift was made to a combination of mail review and a formal peer-review panel.

• Approximately one-third of the funds support the observatory operations at NASA's 3-meter Infrared Telescope Facility, the University of Hawaii 2.2-meter telescope on Mauna Kea, the University of Texas 2.1-meter and 2.7-meter telescopes at McDonald Observatory, and the Arecibo radar telescope of the National Astronomy and Ionosphere Center. All these facilities are available to the general observer community.

• Figure 3 depicts the distribution of funding for FY 1987 by organization. Approximately one-quarter of the funds are spent at NASA Centers, mainly the Jet Propulsion Laboratory. (These funds support the planetary astronomy research activities of NASA Center scientists.) More than one-third of the funds go to universities. Some of the university support is for the extra research costs (such as travel, computer time, research assistants, and summer salary) of scientists who are tenured faculty and whose salary is paid by the university or state government. But about half the university-based scientists are estimated to be on "soft money," which means that the full annual salaries (or a pro-rated share) of the principal investigator and co-investigators are also paid for by the grant. The remaining funds support research activities at non-university institutions, including private observatories and profit and non-profit organizations.

• Compared to the rest of the U.S. astronomers, a high proportion of planetary astronomers are in soft-money positions with the universities, at the Jet Propulsion Laboratory, or in private research institutions. A substantial fraction of the principal investigators in the program, including senior scientists, depend on their NASA grants for their own salaries, a circumstance that generates strains in the Planetary Astronomy Program and magnifies the impact of even minor cuts in funding levels.

• The allocation of funding can be viewed in terms of area or activity. Each of three separate topical areas—outer planets and satellites, comets, and asteroids—receives about one-quarter of the funds. Inner planet studies receive a smaller fraction of funding, and a small but growing fraction of support goes to research directed toward discovering planets around other stars. (See Figure 4.)

• Some funds are reserved for three important supporting activities—theory, laboratory studies, and instrument development—but, in fact, little has been spent on these topics in recent years.

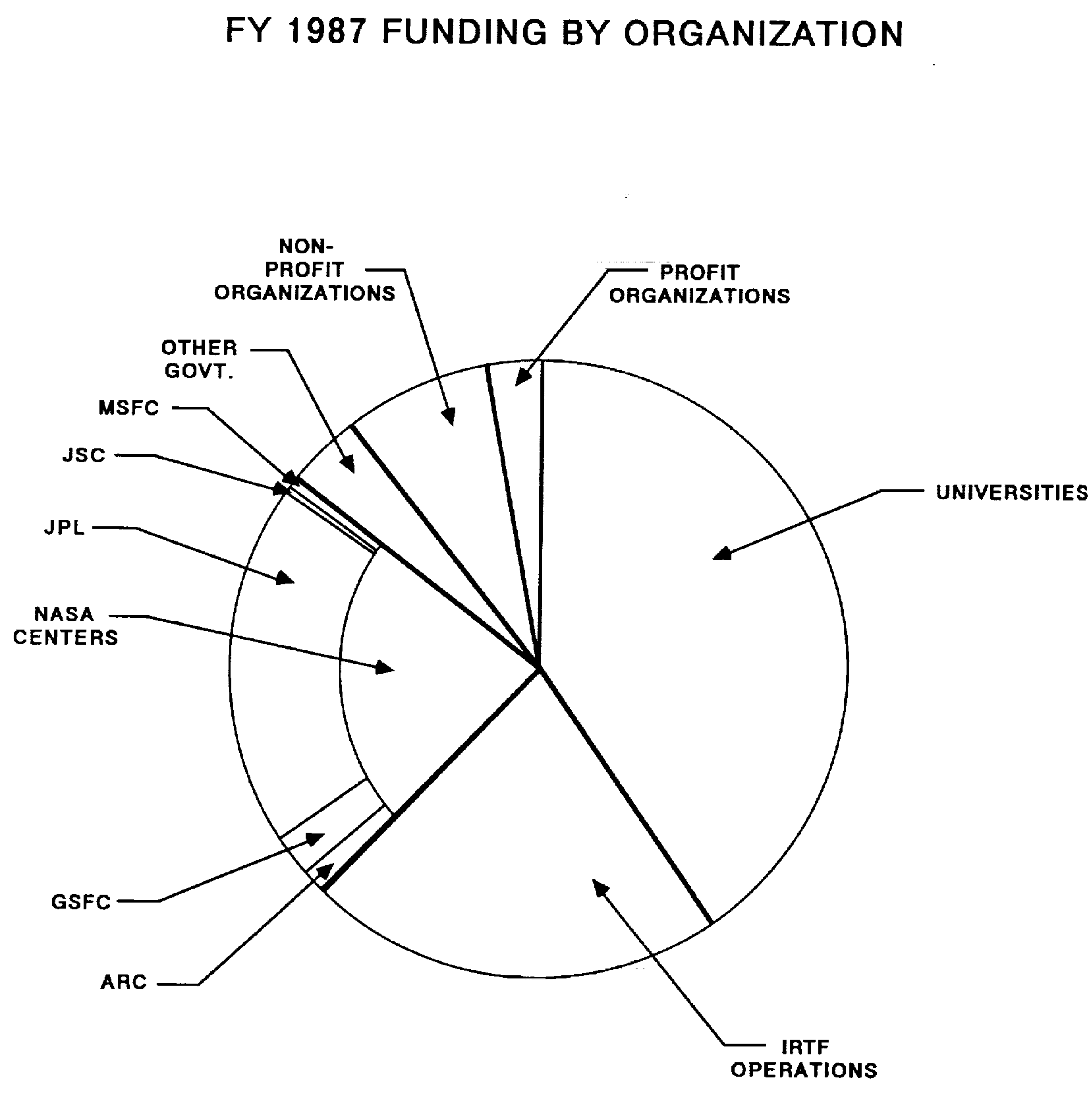

FY 1987 FUNDING BY ORGANIZATION
NON-PROFIT ORGANIZATIONS
PROFIT ORGANIZATIONS
OTHER GOVT.
MSFC
JSC
JPL
NASA CENTERS
UNIVERSITIES
GSFC
ARC
IRTF OPERATIONS

Figure 3

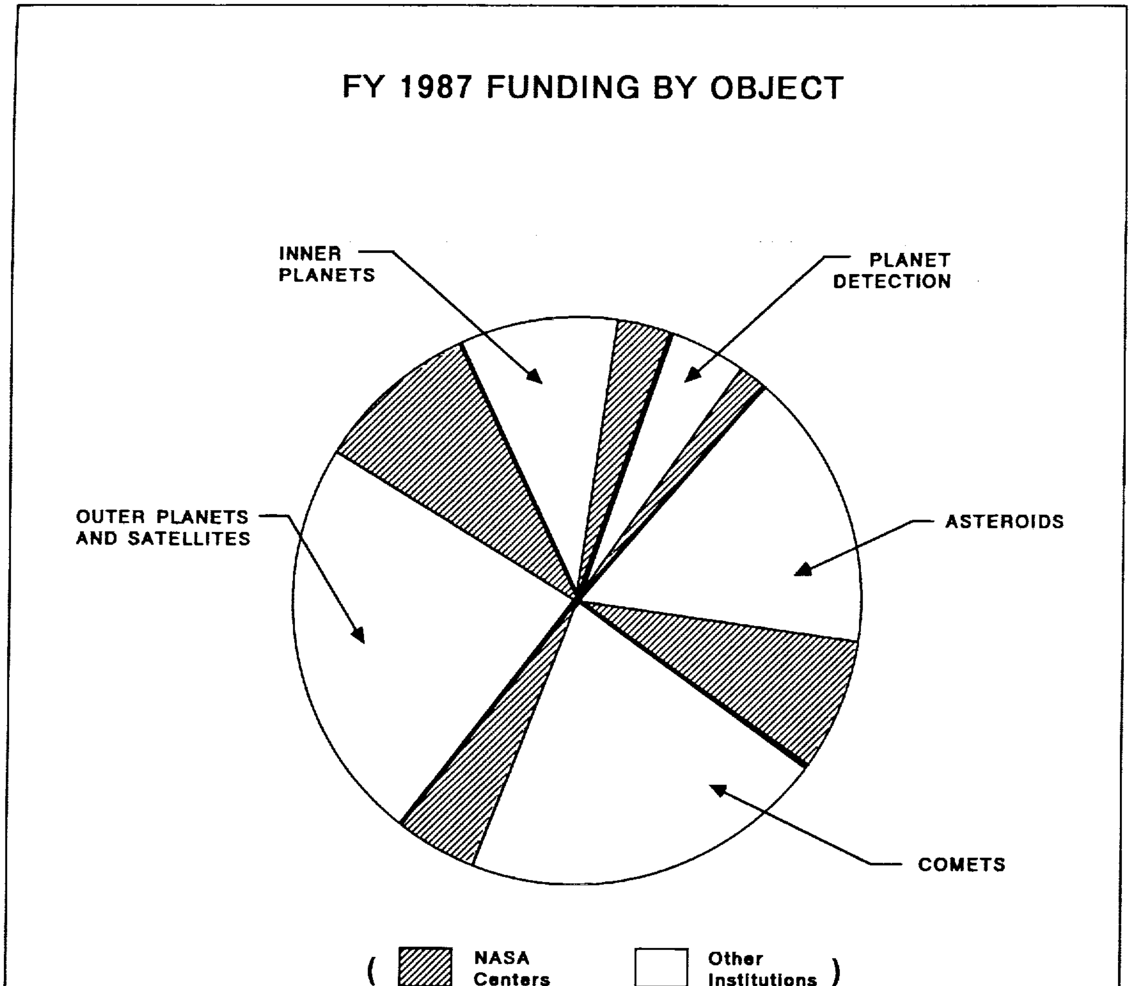


Figure 4

• The allocation of funds can also be broken down by technique. Most planetary astronomy research is done in the visible or the infrared region of the spectrum. A small, but potentially growing, area is research in the ultraviolet region. Radar is another important technique for planetary research; a modest fraction of Arecibo support comes from the Planetary Astronomy Program, and considerable radar research is supported at the Jet Propulsion Laboratory by Deep Space Network activities. Planetary radio astronomy was once a major activity; however, funding in this area was reduced several years ago, and activity has diminished accordingly.

Naturally, the nature of planetary astronomy research has evolved over the years. An earlier concentration on the Moon and the nearby planets has given way to an increased emphasis on planetary satellites, the outer planets, asteroids, and comets. Spacecraft missions have usurped some ground-based capabilities for studying the Moon and some of the nearer planets. The interest in small bodies that is stimulated by ongoing and planned missions to these bodies has been another motivation for redirecting research activities. New instrumental capabilities have also made it possible to study fainter (i.e., smaller and more distant) objects better than in earlier days. Finally, the return of Comet Halley contributed to a recent surge of cometary research.

The Planetary Astronomy Committee has compared the current (FY 1988) budget for the Planetary Astronomy Program with equivalent figures covering the past decade. Although approximately level in constant-value dollars, the budget over that period of time has nonetheless gradually declined by nearly 20 percent, reflecting a general budget squeeze in the NASA Solar System Exploration Division. Within Planetary Astronomy, the core efforts in visible and infrared observing (including operations support for telescopes) have held their own, and the smaller efforts in ultraviolet research and planetary detection have shown a substantial increase. However, cuts have been made in planetary radar, instrument development, theoretical studies, supporting laboratory research, and planetary radio astronomy. In addition, efforts to support young researchers entering the field have had to be made at the expense of ongoing grants, generating additional budgetary stress.

Areas of Concern

The degree to which the changes just discussed reflect conscious policy is not clear. However, the failure of many grants to keep pace with inflation and the extreme difficulties experienced by young investigators trying to establish themselves have clearly had serious consequences on research productivity and on the morale of existing or prospective planetary astronomers. The NASA research cuts have come during a time when alternative sources of funding have been declining as well. First, the well-publicized budgetary hardships of universities affect all disciplines. Second, many planetary astronomers who expected to be deeply involved in spacecraft missions by this time, must, in the hiatus after the *Challenger* accident, seek their funds from research and analysis programs like Planetary Astronomy until new missions can be initiated.

The drop in support in the early 1980s for key supporting activities —theory, laboratory work, and instrument development—seemed at the time to be a fairly painless way to handle what were first thought to be temporary budget problems. Now, however, this drop in support presents planetary astronomy with a real crisis. Practically no instrument development work has been supported in the past few years, despite continuing advancements in detector and computing technology. The fact that modern instrumentation could improve the efficiency of data acquisition by factors of many is axiomatic, but such instrumentation simply has not been funded.

The natural response of scientists to budget reductions is to cut back on the supporting elements that are often essential for maintaining cost-effectiveness and efficiency in their research programs. Students and research assistants can effectively augment productivity at a low cost, but they are the first to go when budgets are cut. Similarly, relatively modest investments in powerful, inexpensive computers also cannot be afforded.

Many of the problems enumerated above for NASA's Planetary Astronomy Program have counterparts in other planetary science disciplines, and in space science generally in the 1980s. But planetary astronomy has additional special problems that need to be addressed. For example, many planetary astronomers rely on large facilities, such as observatories or airplanes, to acquire their data. But with the exception of the Kuiper Airborne Observatory, allocation of observing time to use these facilities is independent of an individual's research funding. A long tradition in astronomy allocates telescope time on a quarterly or semiannual basis by telescope allocation committees, based on separate proposals to each observatory. Even in the case of the NASA Infrared Telescope Facility, this tradition means that proposers find themselves in double jeopardy. They must write separate proposals for funding and for telescope time, and the separate evaluation processes and different timing make coordination difficult. Cases of planetary astronomers being awarded telescope time but no funding, and of being awarded funding but turned down for the telescope time required to accomplish the funded research, are not infrequent. Furthermore, the traditional allocation of telescope time for fixed stellar and galactic objects is mismatched to the flexibility required by many planetary observing programs due to the changing motions of planetary bodies and the rapid variability of their phenomena.

Areas of Strength

All the above problems notwithstanding, NASA's Planetary Astronomy Program has had a remarkable history of continuing productive research. Since the mid-1960s, the prediction has frequently been made that spacecraft missions would render ground-based astronomy obsolete; however, discovery after discovery continues to be made. This fact is partly a reflection of a normal inability to forecast future discoveries. But it also reflects advancements in state-of-the-art instrumentation, which have continually increased detector sensitivity, and spectral and spatial multiplexing, which have opened new planetary vistas to the ground-based telescope. Furthermore, spacecraft results have demonstrated new areas ripe for ground-based observation. Ground-based discoveries, such as hot spots on Io, have been spurred by the approach of a spacecraft to a planet, and discoveries have been made by spacecraft of phenomena, like Jupiter's ring, that can be observed subsequently from Earth. Planetary astronomy has played an especially vital role in determining the composition of solar system bodies. Numerous chemical species, which have not even been detected by *in-situ* spacecraft, can still be most sensitively studied from Earth. And finally, astronomical studies provide the long time base that is essential for understanding many variable phenomena in planetary science. A spacecraft encounter usually generates the equivalent of a detailed snapshot, but only continuing astronomical studies can provide the temporal context required to understand all of the phenomena revealed in this snapshot.

With the increasing interest in primitive bodies and the origin of the solar system, the importance of another attribute of Earth-based astronomy is coming to the fore—its ability to study a whole dispersed population of comets and asteroids and permit generalization to the ensemble from detailed measurements (for example, by spacecraft) of particular examples. Observations of comets and asteroids, and especially of the fainter members of these groups, have assumed an important place in planetary studies.

Although in recent years attention has been diverted from the Moon, Mercury, and Mars, we have every reason to expect that even these nearby worlds are susceptible to further useful scrutiny using Earth-based techniques. The development of Earth-orbiting observatories opens a new potential for exploiting the unique advantages of space-based observation, including access to the ultraviolet and infrared wavelengths, which are otherwise blocked by gases in Earth's atmosphere, and the possibility of diffraction-limited observing. Both ground-based and airborne astronomy have considerable potential for improvement, as well. For example, recent tests suggest that the inherent seeing conditions at Mauna Kea are even better than had been thought, and the SOFIA project offers gains in light grasp and image quality that will significantly augment the capability of the current Kuiper Airborne Observatory.

Ground-based, airborne, and Earth-orbital planetary astronomy provide a wealth of new, important data at very low cost as compared with space missions. The program can take advantage of the astronomical infrastructure supported by other agencies, institutions, and facilities, and it could profit greatly from continuing technological developments. However, funding constraints and redistribution in recent years have seriously restricted the realizable potential of planetary astronomy. If planetary astronomy is not to stagnate, if it is to take advantage of modern advances in computers and detector technology, and if it is to be a broad endeavor involving interpretation and analysis of data in addition to simple data acquisition, then an infusion of new money into the NASA Planetary Astronomy research and analysis program is required. No other division of NASA, or any other governmental agency, has the capability or commitment to Earth-based planetary astronomy to provide more than ancillary contributions to the field. Better coordination with these other agencies is very important, but the core support for planetary astronomy in the 1990s must come from NASA's Solar System Exploration Division. The new infusion of funds should be directed primarily toward:

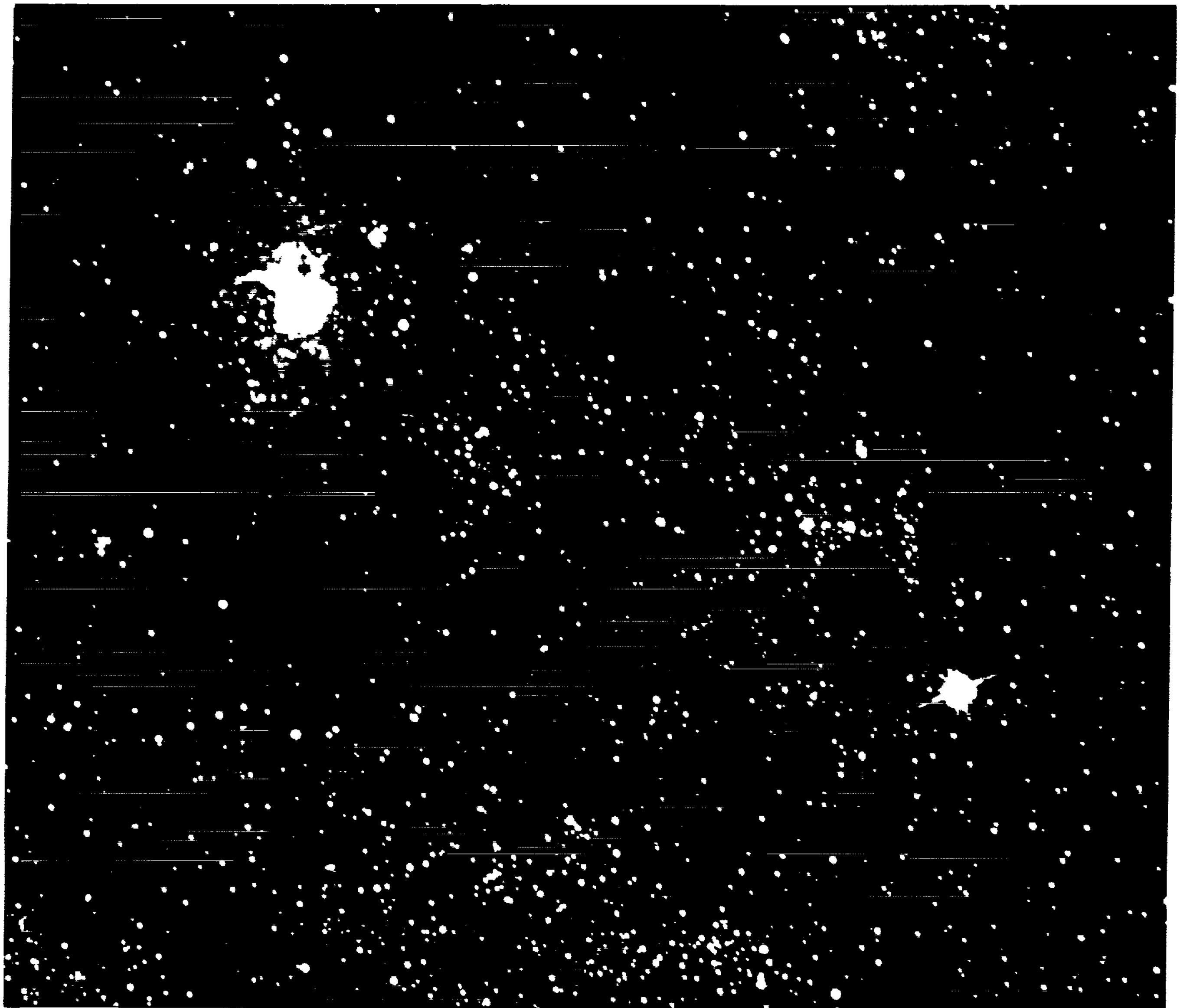
- Revitalizing the infrastructure of existing research groups;

- Encouraging student involvement in planetary astronomy and providing the opportunities for new researchers to enter the program and apply their creativity to planetary astronomy;

- Reestablishing the programmatic elements of planetary astronomy that have been squeezed (or squeezed out) in recent years, so that the field has a disciplinary balance, including the important activities of associated laboratory and theoretical research; and

- Taking major steps to develop new state-of-the-art instruments to use for planetary research, which will permit observations that were never before possible.

Supernova 1987a in the Large Magellanic Cloud appears as a very bright object near the lower right of this photograph, taken from the National Optical Astronomy Observatories' Cerro Tololo Inter-American Observatory.



Ground-Based and Airborne Planetary Astronomy

Although spacecraft missions have revolutionized our understanding of the solar system, spectacular contributions to our knowledge have also been made with ground-based and airborne investigations during the past few decades. These discoveries have resulted from the fact that the planetary astronomy community has used to its advantage several characteristics of Earth-based observations: (1) short cycle time between the inception and execution of an investigation; (2) opportunity for immediate modification of observing plans in response to knowledge gained from the data being acquired; (3) rapid incorporation of state-of-the-art detectors into instruments; (4) easy infusion of new ideas and techniques from a broad community of scientists; (5) ability to use facilities (telescopes and instruments) created by other disciplines; and (6) scientific work that can be done by one person or a small group of individuals, which is appealing to students and new Ph.D.s.

Observational Techniques

Most of the observational techniques, related instrumentation, and scientific goals for telescopic observations of solar system bodies are the same, whether the telescopes are located at ground-based observatories or in aircraft. The principal differences between ground-based and airborne observational studies lie in the wavelength regions covered (airborne platforms are less encumbered by atmospheric absorption), and the possible size of the telescope for optical work (0.9 meter in the Kuiper Airborne Observatory versus up to 6 meters on the ground).

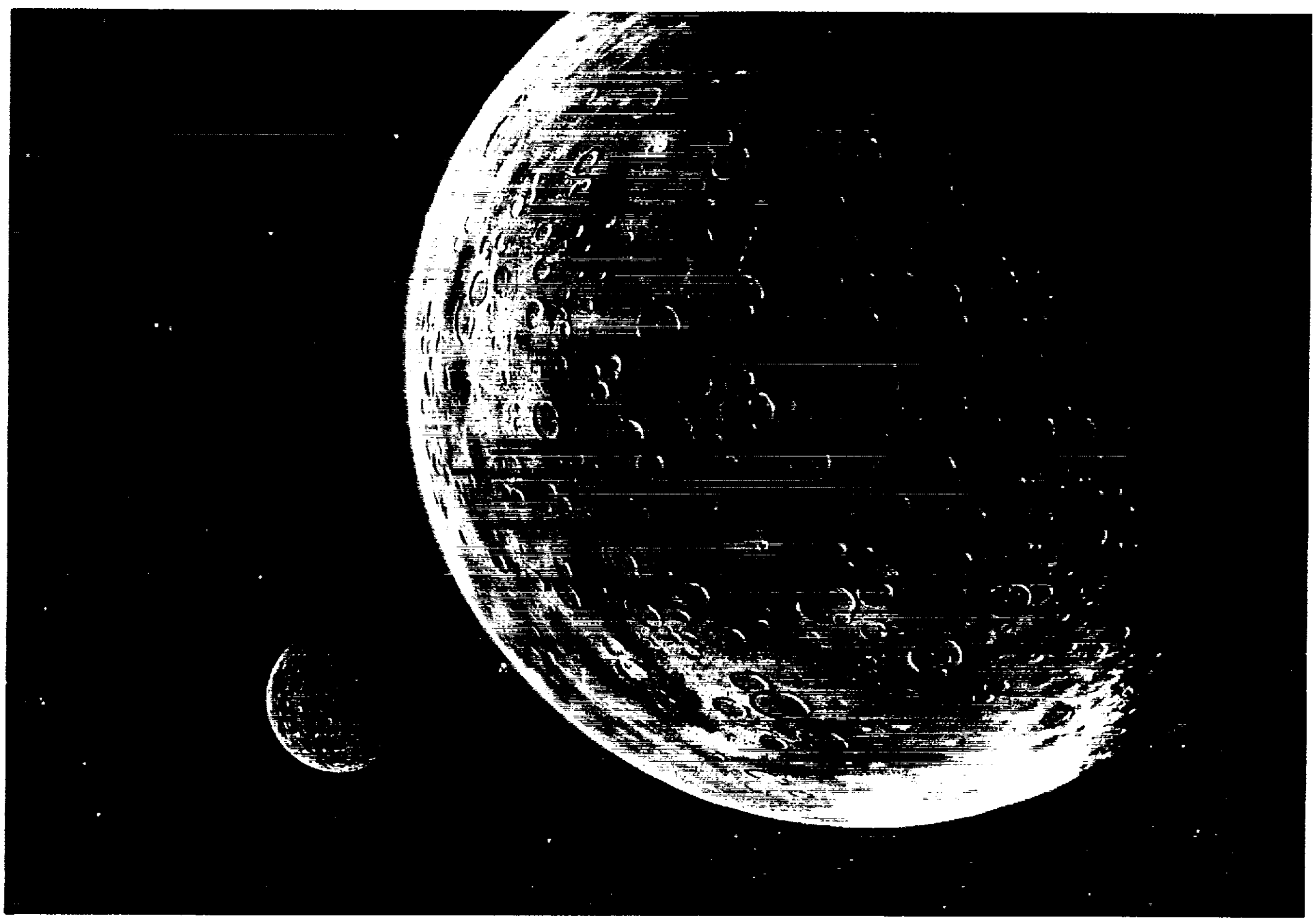
The cost of operating an airborne observatory greatly exceeds that of a large ground-based telescope, and observing periods are limited to the few hours during which the aircraft can be properly positioned for observations of a specific object. These two factors restrict airborne observations to those spectral regions that cannot be studied from even the highest mountaintop observatories, or to measurements of unique phenomena, such as eclipses or occultations, that are time-dependent or related to geography in such a way that no ground-based observatories can see them.

Photometry and Radiometry

Photometry, the observation of brightness changes in solar system bodies with time, or as a function of illumination or observing geometry, remains a vital source of information. Long-term global variability in the atmospheres of the outer planets and of Saturn's moon Titan, and the relationship of this variability to the solar cycle, are subjects of growing importance. What we know about the rotation periods, gross shapes, pole orientations, and surface properties of asteroids is derived largely from optical photometry, although more refined information is becoming available for the nearby asteroids that can be investigated with radar. Pluto and its satellite, Charon, are being studied extensively by photometric methods during the epoch of mutual eclipses, transits, and occultations to derive the satellite's orbital parameters and the radii of the planet and satellite. Photometry is also being used to make rudimentary maps of the distribution of methane frost and the other materials comprising Pluto's surface. Comets are studied by photometric techniques with specially designed filters to isolate the continuum and the emission bands; photometry gives information about the dust and about the production rates of various gases.

Observations of solar system bodies in the near infrared spectral region where reflected sunlight dominates (1 to 3 micrometers) are useful for first-order information on surface compositions of airless bodies through broadband colorimetry. This technique is particularly relevant to those objects that are too faint to permit spectrophotometric studies. In the thermal infrared, where the bodies' own radiation dominates the observed flux, numerous solar system objects are of continuing interest. A prime example is Io's spatially and temporally variable thermal flux, which is caused by the changing eruptive status of its numerous volcanoes. Other planetary satellites under tidal stress—Europa, Enceladus, Mimas, and Triton—may also exhibit exothermic phenomena that can be studied by infrared astronomical techniques. The night side of Venus shows continually changing patterns of infrared radiation, presumably surface emission leaking out through clouds of variable opacity in the lower atmosphere. Charting the changing patterns may soon provide us with the best evidence about circulation patterns in the lower atmosphere of Venus. The surface thermophysical properties of solid bodies, such as planetary satellites, asteroids, and some comets, are also studied radiometrically, and theoretical modeling is keeping pace with the increasingly sensitive observations of these bodies.

The thermal budgets of the major planets are subjects of continuing interest and importance. The ground-based studies are integrated with thermal data returned from planetary probes, such as *Mariner, Viking,* and *Voyager,* to study the long-term thermal properties of the

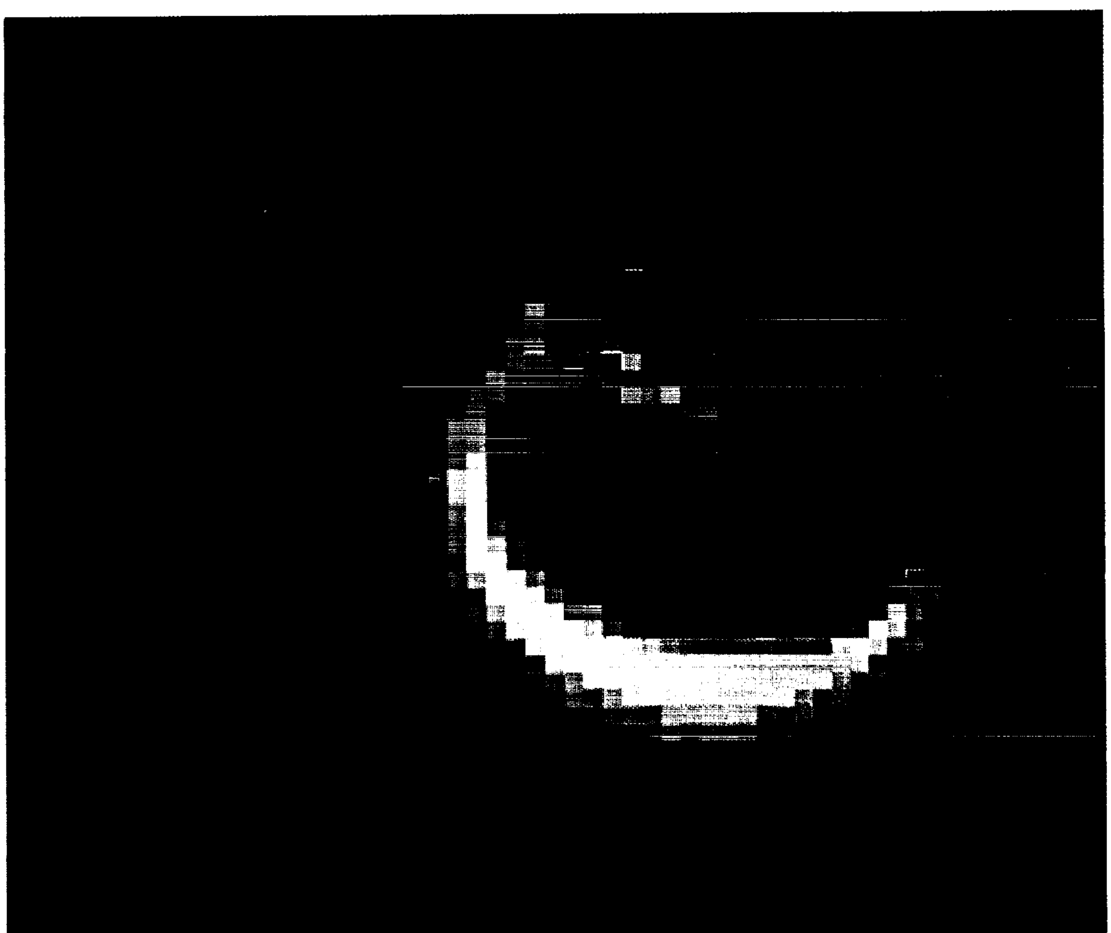


Pluto and Charon are extraordinary objects that have been extensively studied by ground-based astronomers.

atmospheres of Venus, Mars, Jupiter, and other outer planets. Maps of these planets made at thermal infrared wavelengths are showing the distribution of such atmospheric phenomena as aurorae.

Spectrophotometry

Spectrophotometric studies seek to establish the energy distribution of reflected sunlight from a planetary body at a higher spectral resolution than that afforded by discrete broadband filters. Such studies can also be done in a spatial mapping mode (e.g., for the Moon and Mars), and these studies have laid the foundation for a new generation of spaceborne spectrometers—the Near Infrared Mapping Spectrometer on *Galileo,* and the Visible Infrared Mapping Spectrometer on the *Comet Rendezvous Asteroid Flyby*. Many small solar system bodies, including comets, asteroids, planetary satellites, and Pluto, are studied by spectrophotometry. Visible and infrared spectrophotometry (0.3 to 3.5 micrometers), carried out from exceptionally dry sites, is particularly sensitive to condensed-phase constituents on the surfaces of satellites and asteroids. Broad



This Pioneer Venus *false-color image shows atomic oxygen auroral glows on the night side of Venus, within its sunlit crescent.*

absorption bands of various minerals and condensed volatiles are found in the low-resolution spectra of many of these bodies; igneous rock-forming minerals such as the pyroxenes and olivine have been found on many asteroids, whereas frozen sulfur dioxide, water, and methane have been found on various planetary satellites and also on Pluto.

Spectroscopy

Spectroscopy is a fundamental source of basic information about the compositions and structures of planetary atmospheres, the composition of comets, and the physics of planetary coronae. Spectral resolving powers ($R = \lambda/\Delta\lambda$) from 10^3 to 10^7 are possible with a variety of instrumental techniques presently being applied in the visible, near-infrared, and mid-infrared regions. Conventional visible region spectrometers ($R = 10^3$) equipped with modern detectors, such as charge-coupled devices or Reticons, are supplemented by echelle spectrometers ($R = 10^5$) using two-dimensional detectors. Fabry-Perot spectrometers yield $R = 10^4$, and Fourier transform spectrometers offer $R = 10^5$. Using heterodyne techniques, the resolution can be increased another factor of 10 or even 100.

The highest spectral resolution (on the order of 10^7) is now being used to study the upper-atmosphere winds on Mars and Venus, to search for global oscillations on Jupiter, and to establish the mass loss from comets. When 10 or more resolution elements may be obtained across a spectral line originating in a planetary atmosphere, inversion of the radiative transfer equation for the formation of the line yields information on the atmospheric structure of the planet. Line intensities, which can be measured at lower resolutions, yield rotational and kinetic temperatures in planetary atmospheres, and this information can be applied to problems of atmospheric circulation when the data are obtained with spatial resolution, as in the belts, zones, and spots of Jupiter. New atmospheric constituents can be sought at various spectral resolutions and in various specific bands.

Imaging

As in the earliest days of astronomical photography, imaging of solar system bodies continues to play a vital role. With the development of two-dimensional detectors with wide dynamic range and extended sensitivity, this technique will be used for the expanded study of atmospheric structure, the rings of the major planets, atmospheric aurorae, and extended coronae. The structure of cometary comae is explored in the visible and infrared regions, and direct imagery is used to search for new comets, asteroids, and planetary satellites.

Infrared and visible imaging are also of prime importance for the study of star formation processes. Stars, and by inference, their planetary systems, form in regions of dense interstellar dust, which normally blocks the escape of visible and ultraviolet radiation. Only in the infrared are these dust clouds sufficiently transparent to permit investigation of the process taking place. Even in nearby star-formation regions, the typical spatial scales of these dust cocoons are on the order of an arcsec, so that excellent image quality and large apertures are essential for such investigations.

As imaging dectectors improve, so do the techniques for their use. Computer algorithms for image restoration and related techniques of seeing compensation during measurements at the telescope, all with the goal of improving spatial resolution, continue to be developed. Radar delay-doppler imaging techniques have long been used to map Mercury and Venus, and these techniques are now beginning to be applied to asteroids, which generally cannot be resolved with optical instruments. More sensitive radars could also image the nuclei of short-period comets with a resolution of a few hundred meters.

New techniques of imaging in the visible and infrared, using speckle interferometry, are being developed and applied to solar system studies. This technique has shown great promise in the context of the volcanoes on Io, where the interferometric technique has shown the location and relative fluxes of unresolved hot spots. Speckle images provide rudimentary visualization of the albedo distributions on asteroids, and have yielded resolved images of Pluto and its satellite that permit the determination of Charon's orbital parameters.

Polarimetry

Polarimetry in visual wavelengths has long been used in planetary research for the study of both atmospheric particulates and the surface characteristics of airless bodies. Perhaps the greatest success in the ground-based application of polarimetry to observing planetary atmospheres was the derivation of the refractive index of Venus's cloud particles, which led to the discovery that they were composed of sulfuric acid droplets. The technique has been extended to the thermal infrared for studies of Io's volcanic phenomena, and continuous monitoring of these phenomena has been shown to be possible into the indefinite future, affording the opportunity to observe the evolution of volcanism on a body other than Earth.

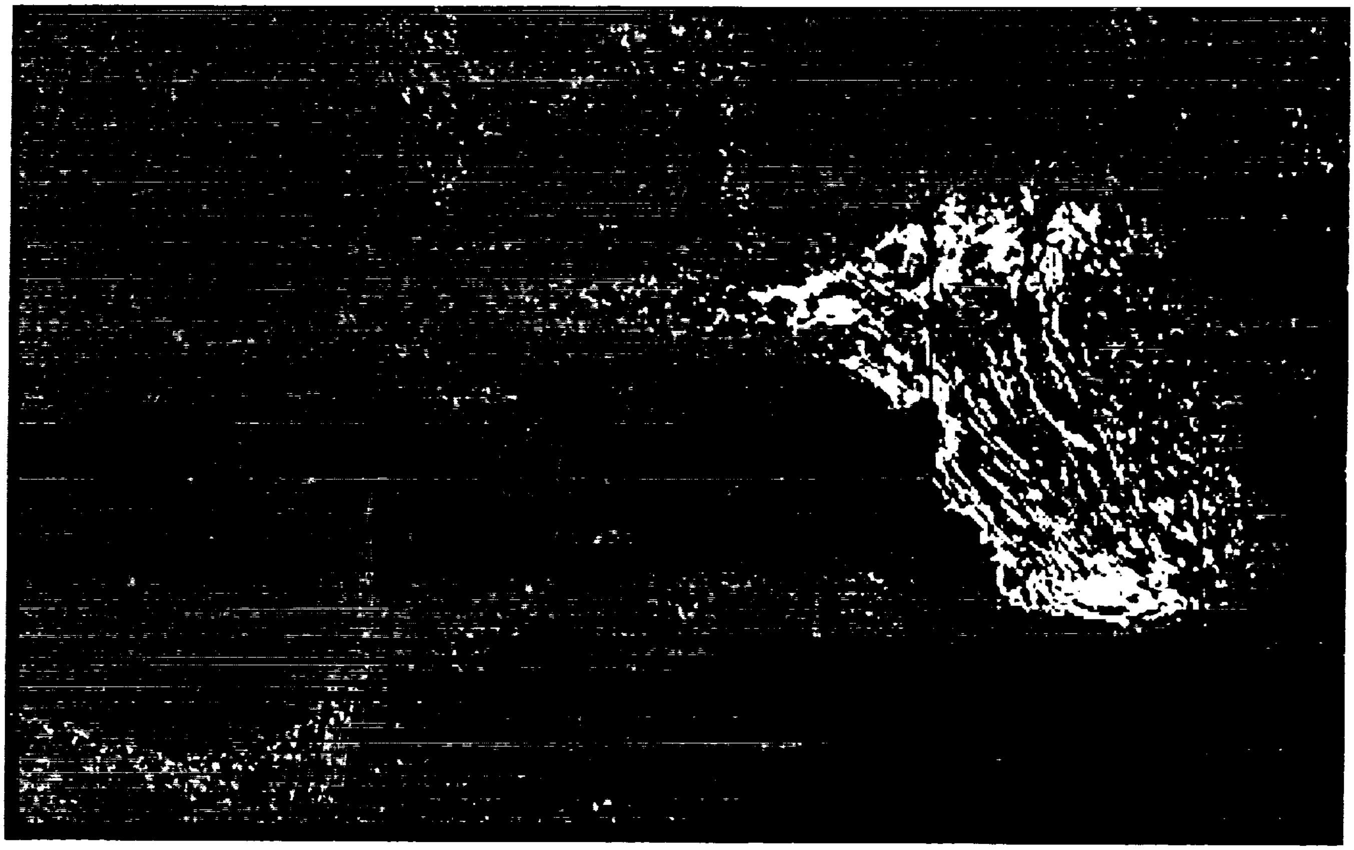
Occultations

Because of their excellent spatial resolution—4 kilometers at Uranus, for example—observations of stellar occultations by planetary bodies have opened new windows on several important problems that cannot be addressed by any other technique presently available. Chief among these are: (1) the study of the thermal structure of planetary upper atmospheres; (2) the precise measurement of the sizes and figures of planets, satellites, and asteroids; and (3) the investigation of the structure and kinematics of planetary rings, which has led to advances in our understanding of their dynamics.

Observations of stellar occultations by the major planets yield temperature and pressure profiles of the upper atmospheres to a depth corresponding to a pressure of about 10 microbars. Prior to the *Viking* entry probes, this technique was used to discover the inertia-gravity waves in the upper atmosphere of Mars. Occultations by asteroids continue to provide the most accurate measurements of their sizes and shapes, thereby serving to calibrate the more widely applicable techniques. Occultations by large planets are used to derive planetary figures that bear directly upon their internal structures.

The rings of Uranus were discovered by simultaneous airborne and ground-based stellar occultation observations, and have since been

Radar studies of Venus revealed the presence of mountains on Earth's twin planet. This Arecibo radar map shows the Maxwell Montes, which cap the Ishtar continent.



studied both from Earth and *in-situ* by *Voyager 2*. Additional work is required to complete the orbital models of several of the rings, and further data will be needed to understand the dynamical evolution of the ring system and its shepherd satellites. Similarly, additional studies of Saturn's rings are needed to integrate the Earth-based data with those from *Voyager*. Neptune's "ring-arc" system is apparently unique; even after *Voyager's* encounter in 1989, the only way to continue observing this system at high spatial resolutions will be through its occultation of stars.

Radar

Radar is a powerful technique that is currently being exploited to derive otherwise unobtainable information about solar system bodies. The advantages of this technique result from: (1) the observer's control of all the attributes of the coherent signal, especially the time and frequency structure and polarization, used to illuminate the target; (2) the ability of radar to resolve objects spatially (corresponding to time delay and doppler frequency shift of returned echo); and (3) the centimeter-to-meter radar wavelengths, which easily penetrate planetary clouds and cometary comae and permit investigation of the near-surface macrostructure, bulk density, and metal concentration in planetary regoliths.

During the 1960s, radar refined our knowledge of the astronomical unit and ensured successful guidance of the first interplanetary space probes. Radar revealed the true rotational spin of Venus and Mercury, and furnished the earliest indications of the topographic diversity of

Mars. Venus has been imaged at increasingly finer resolution since the late 1960s, and the best U.S. ground-based radar maps compare favorably with orbital radar from the U.S.S.R's *Venera 15* and *16* spacecraft. Radar detection of Saturn's rings helped to confirm that they are composed of water ice, and disclosed that a large fraction of the ring particles are at least one centimeter in size. More recently, radar observations have yielded a wealth of new information about the physical properties of several comets and several dozen asteroids. The first direct detection of a cometary nucleus in 1983 was followed by the discovery of large-particle clouds associated with Comets IRAS-Araki-Alcock and Halley.

The radar signatures of near-Earth asteroids are extraordinarily diverse, and they reveal that a number of these small objects have extremely irregular, non-convex shapes. For two decades, radar refinement of orbits has been important for maintaining the accuracy of inner-planet ephemerides. This capability is critically important for newly discovered Earth-approaching asteroids, since the detection of radar echoes can guarantee the recovery of asteroids on subsequent apparitions.

Planetary radar astronomy is limited by the sensitivity of existing telescopes. Relatively modest improvements in these facilities will greatly affect the ability to extend radar investigations to smaller and more distant objects. This technique is on the threshold of producing an enormously valuable body of information about asteroids, comets, and natural satellites.

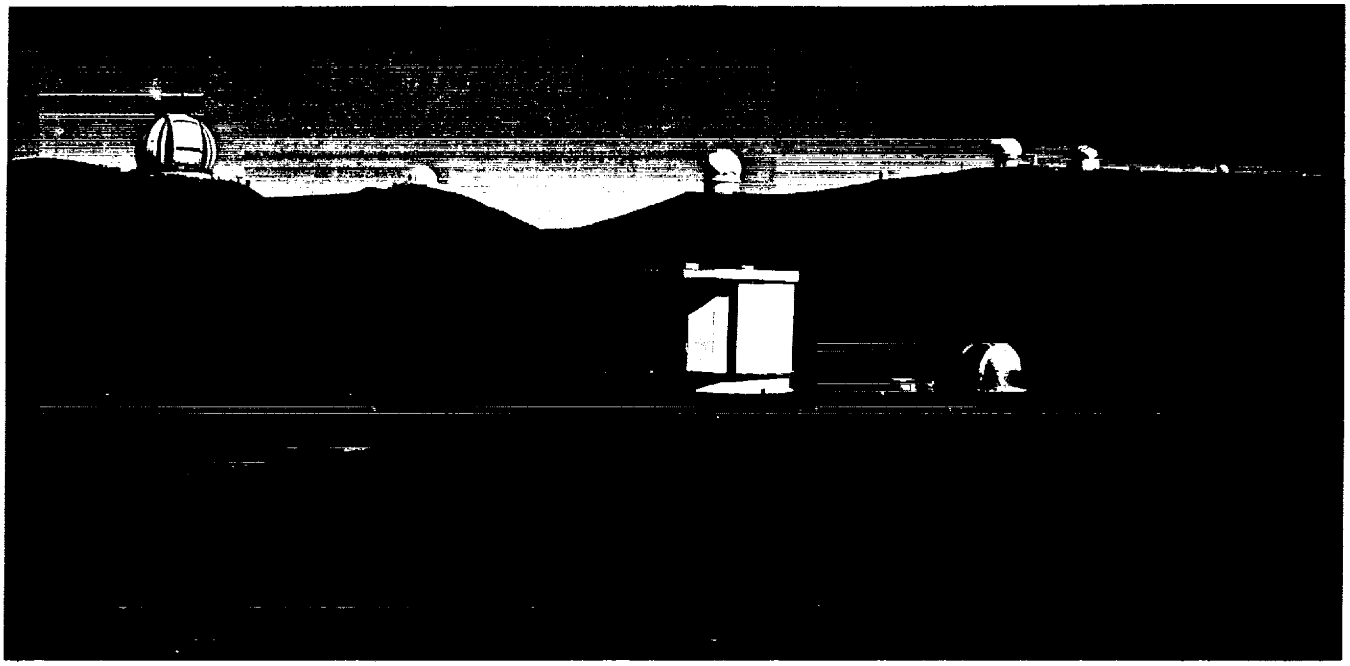
Searches for Other Planetary Systems

Two ground-based techniques—astrometry and doppler spectroscopy—are being used to search for the presence of objects of sub-stellar mass (planets or brown dwarfs) from the reflex motion these objects induce in the stars they orbit.

Astrometry from ground-based telescopes is the century-old classical method of position and orbit determination for all solar system bodies and for binary stars, as well as for the more recent search for companions in orbit around other stars. Technological advances in the last decade, such as replacing the photographic plate with electronic detectors, have improved astrometric precision by an order of magnitude, making this technique far more effective in the search for other planetary systems. The time scale for detection remains long (years to tens of years) because of the slow motions of planets around their stars, and the technique is sensitive primarily to massive (Jovian) planets orbiting nearby low-mass stars. To date, the new astrometric technologies have not been applied at sites with excellent seeing, which would greatly strengthen the power of the technique.

High-resolution doppler spectroscopy is capable of determining the radial component of the reflex motion of a star to a precision of 10 meters per second or better. This provides a second ground-based technique for the detection of massive planets around other stars. Observing programs encompassing about two dozen stars are under way at the Canada-France-Hawaii Telescope, the University of Arizona, and elsewhere. These studies, unlike astrometry, are appropriate to ground-based telescopes with large apertures and cannot be greatly improved upon from space.

At an elevation of almost 14,000 feet, Mauna Kea in Hawaii is an excellent site for astronomical observations. This photograph shows some of the several telescopes that are located there.



Both the ground-based astrometric and doppler-spectroscopic approaches to the detection of extrasolar planets will play important roles in the developing survey of nearby stars to derive the fundamental statistics on the occurrence of planetary bodies beyond our own solar system. The potential and special advantages of each approach are discussed in more detail when we turn to the future needs of planetary astronomy.

Facilities for Ground-Based and Airborne Planetary Astronomy

Ground-Based Optical/Infrared Telescopes

In the 1960s, three moderate size telescopes were built with NASA funds to further the aims of planetary astronomy and to provide ground-based support for NASA's planned missions to the Moon and the planets. These telescopes are the Arizona 1.5-meter telescope, the Hawaii 2.2-meter telescope, and the Texas 2.7-meter telescope. In the 1970s, in response to the need for a dedicated infrared telescope located at a superior observing site, NASA funded the construction of the 3-meter Infrared Telescope Facility at Mauna Kea in Hawaii. These four telescopes account for more than half the total time available for solar system work on instruments of 1.5-meter or larger aperture, and they are the mainstay of planetary astronomy studies in the visible/infrared region of the spectrum.

Other large and moderate telescopes are sometimes used for solar system observations, usually by resident staff in the case of university-owned and operated telescopes, but by visitors in the case of the National Optical Astronomy Observatories. Around the world, approximately a dozen telescopes of 3- to 5-meter aperture are used at least occasionally for planetary work. Many smaller telescopes (about 1 meter) are also used to great advantage.

Projected Ground-Based Optical/Infrared Telescopes

During the early 1990s, we anticipate that a number of new large optical/infrared telescopes will be built. At Mauna Kea in Hawaii, the W.M. Keck Observatory, with a 10-meter telescope, is under construction, with a projected completion date of 1992. In addition, plans for a Japanese telescope of 7.5-meter aperture and for a U.S. national (National Optical Astronomy Observatories) 8-meter telescope at Mauna Kea are being developed. A 4-meter telescope is under construction at Sacramento Peak in New Mexico, and one 4-meter and at least one 8-meter instrument are proposed for Mt. Graham in Arizona. The European Southern Observatory has begun work on a very large instrument with four 8-meter mirrors to be located in South America. Some time for planetary observing is expected on all these telescopes, although not all of them will be open generally to U.S. planetary astronomers.

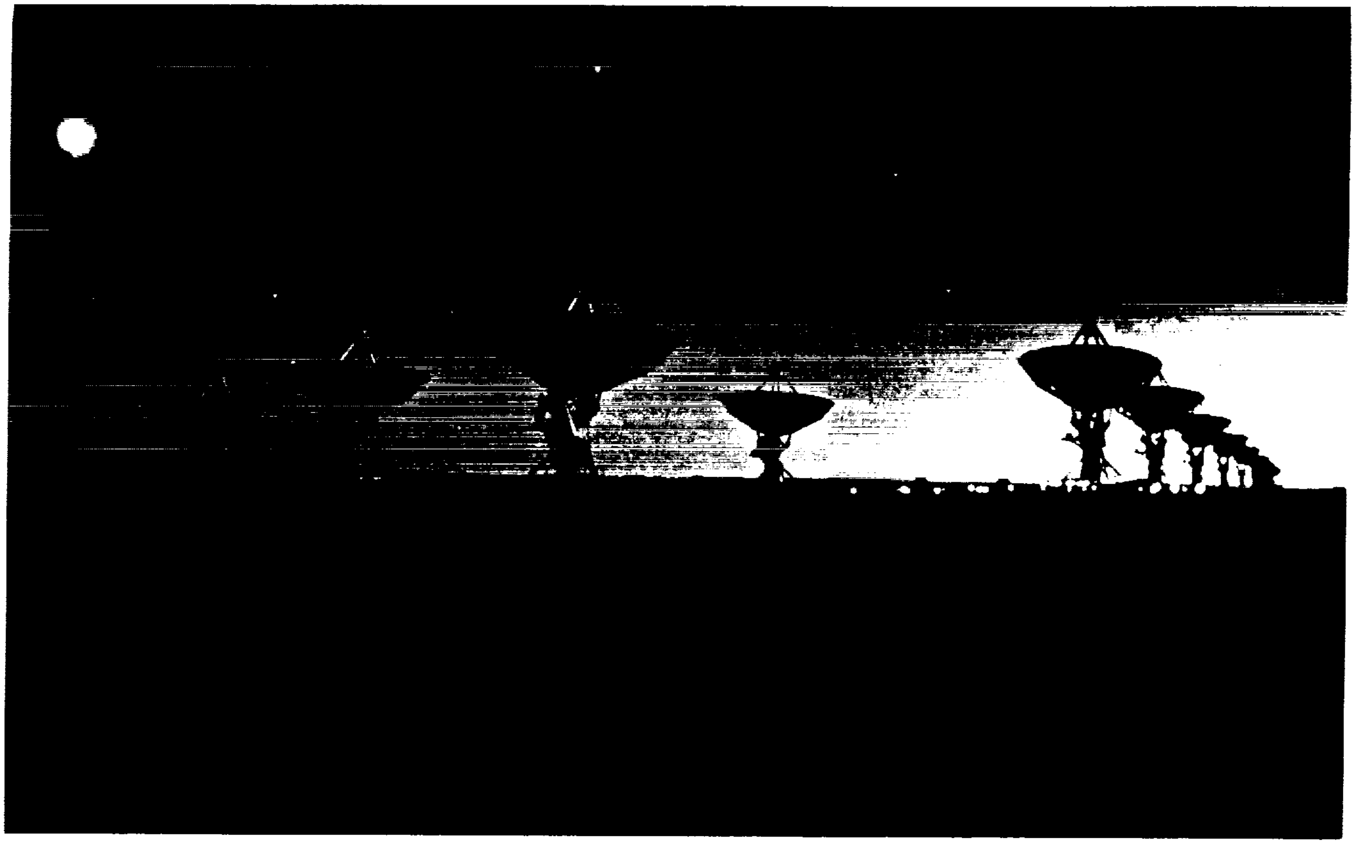
Radar and Radio Facilities

The Arecibo radio-radar telescope is part of the National Astronomy and Ionosphere Center, operated by Cornell University under contract to the National Science Foundation. The Arecibo telescope consists of a 305-meter-diameter fixed reflector, the surface of which is a section of a 265-meter-radius sphere. Movable line feeds designed to correct for spherical aberration are suspended from a triangular platform some 130 meters above the reflector, and they can be aimed toward various positions on the reflector, enabling the telescope to point up to 20 degrees from the zenith (where the declination is 18.3 degrees north). The radar wavelengths used are 13 and 70 centimeters. The availability of an additional receiving antenna allows interferometric observations that can be used to map Mercury and Venus. NASA support in the mid-1970s made possible the installation of the 13-centimeter radar system. Since then, annual support from NASA has proven essential to the continued operation of this facility, which remains the world's most powerful radar for planetary astronomy. As a national center, Arecibo is accessible to the entire scientific community.

The Goldstone radar is part of NASA's Deep Space Network, which is operated by the Jet Propulsion Laboratory. Since the 1960s, the radar has been used almost exclusively by Jet Propulsion Laboratory experimenters, but efforts are under way to make this facility available to the entire scientific community. One important aspect of this initiative is to increase the fraction of Deep Space Network time allotted to radar astronomy.

The Goldstone main antenna is a fully steerable, 70-meter, parabolic reflector with horn feeds. Radar wavelengths used are 3.5 and 13 centimeters, and two additional antennas are available for interferometric observations. Goldstone is one-third as sensitive as Arecibo, but it has access to the whole sky north of -50 degrees declination, and it can track targets continuously for much longer periods. Goldstone's wide declination window is an especially valuable asset for radar reconnaissance of comets and Earth-approaching asteroids; about half of the close approaches of comets and asteroids occur outside the Arecibo window.

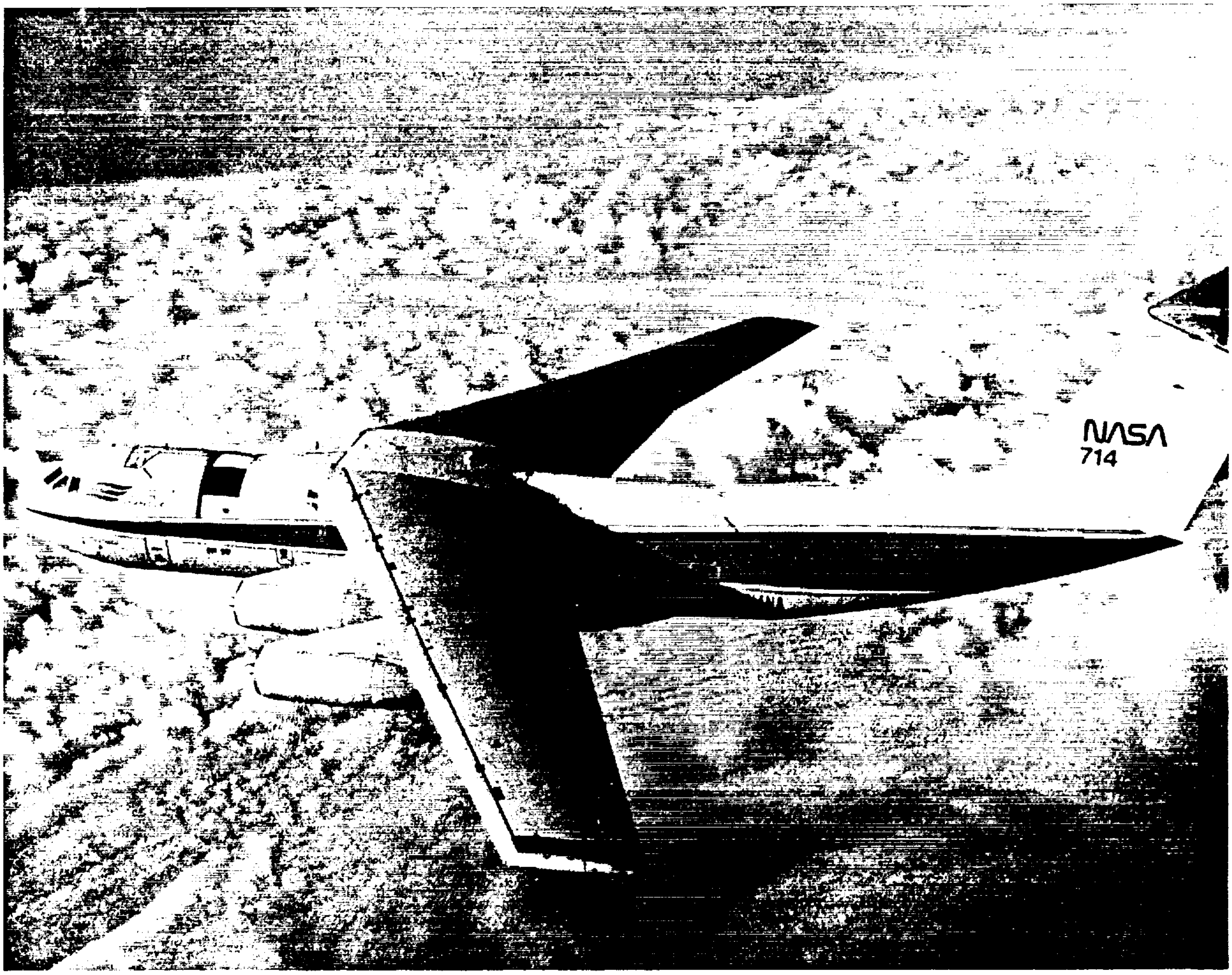
The Very Large Array Observatory in New Mexico
is shown at dusk, with the Moon, Jupiter, Saturn, and the familiar "teapot" of Sagittarius visible in the sky.



With an interferometric array of 27 fully steerable 26-meter antennas, the Very Large Array operated by the National Radio Astronomy Observatory is an extremely powerful radio telescope for the study of certain planetary problems. It has been used for probing the atmosphere of Titan and for observing comets at millimeter to centimeter wavelengths. In addition to its collecting area, the great virtue of the Very Large Array is the angular resolution it can achieve, for example, in separating satellites from their planets, and in probing the comae of comets. This system produces radio views of celestial objects with spatial resolutions comparable to those of the very best optical telescopes.

Airborne Facilities

The Gerard P. Kuiper Airborne Observatory (KAO), with its 0.9-meter telescope in a C-141 aircraft, has been the keystone of NASA's airborne astronomy program since 1975. It flies approximately 75 missions per year, of which 10 to 18 are devoted to planetary astronomy observations. The facility operates at an altitude of 14 kilometers, where atmospheric transparency in the infrared permits photometric and spectroscopic observations in spectral regions that cannot be observed from any ground-based site. Many discoveries in planetary astronomy are credited to scientists using the KAO; the rings of Uranus were found with this facility, as was the emission spectrum of water vapor in Comet Halley, and water deep in the atmosphere of Jupiter. A substantial fraction of KAO flight time is devoted to the far-infrared study of interstellar material and star-formation regions.



The Gerard P. Kuiper Airborne Observatory is a high-flying aircraft that is used primarily for observations in the infrared.

Use of Facilities for Planetary Astronomy

Although a large number of facilities are ostensibly available for planetary astronomy, the bulk of the work is performed with a small number of telescopes of moderate size. The NASA Infrared Telescope Facility in Hawaii is the only large instrument on which a major fraction (50 percent) of the scheduled time is mandated for planetary studies. The oversubscription ratio for planetary projects on this facility varies between 1.5 and 2.5. Other large telescopes used more than 10 percent for planetary work include the Hawaii 2.2-meter, the Texas 2.7-meter and 2.1-meter, and the Arizona 1.5-meter.

In the four-year interval from 1980 to 1983 inclusive, the National Optical Astronomy Observatories telescopes were scheduled for planetary astronomical work for only 2.6 percent of the nights. In the same interval, an average of 13 papers per year on planetary astronomy were published by National Optical Astronomy Observatories staff and visitors, out of approximately 350 to 400 papers. These percentages continue to decline.

The availability of appropriate modern instrumentation for use on telescopes is a critical factor in the use of these facilities for front-line research. Without surveying in detail the situation with regard to modern instrumentation at each of the telescopes listed above, a few general remarks can be made.

1. The NASA Infrared Telescope Facility: NASA supports the operation of this facility at the level of about $2 million per year. By agreement, the National Science Foundation entertains proposals for focal-plane instrumentation for this facility, and two major instruments, a cooled grating array spectrometer and a higher resolution echelle spectrometer, have been funded under this arrangement. However, in infrared imaging and 10 micrometer spectroscopy, the Infrared Telescope Facility has remained behind in state-of-the-art instrumentation.

2. Other NASA-built telescopes: The University of Texas 2.7-meter telescope at the McDonald Observatory is partly supported by NASA funds. About two-thirds of all the observing with this telescope is done with various modern detectors at the coude spectrograph, which was also built with NASA funds. Other instruments have been built with funds from the National Science Foundation and the state of Texas; some of these instruments are used for planetary work. At the University of Arizona, no facility-class instruments are available. Only those built and used by principal investigators can be made available. No current instrumentation initiatives are under way for planetary work on the 1.5-meter telescope. At the University of Hawaii, several facility instruments exist at the 2.2-meter telescope; support for their operation and maintenance comes from a variety of grants from the National Science Foundation and NASA's Planetary Astronomy Program. New initiatives for improved instrumentation (charge-coupled devices, spectrometers) are awaiting funding from both agencies.

Rapid advances in detector technology provide enormous improvements in instrument sensitivity, spectral resolution, and wavelength coverage, but planetary astronomers are often unable to find funds to take advantage of these developments. Much observational work of direct relevance to NASA programs cannot be accomplished because of a serious and long-term lack of fiscal resources required for the construction and implementation of front-line instrumentation for ground-based and airborne telescopes.

Needs for the Future of Planetary Astronomy

Additional Ground-Based Telescopes

Current ground-based telescopes are powerful tools for both the continuing investigation of our own planetary system and for new initiatives in the study of star and planet formation and circumstellar material. In the 1960s and 1970s, NASA initiated the construction of four large optical/infrared telescopes for planetary work. These telescopes are used today for the majority of ground-based optical/infrared investigations of solar-system objects, and all four telescopes are heavily oversubscribed.

The Multiple Mirror Telescope is a large astronomical instrument that combines six 1.8-meter Cassegrain telescopes mounted symmetrically around a central axis with the optical beams brought to a single focus.

Direct observational support for forthcoming planetary missions such as *Galileo,* the *Comet Rendezvous Asteroid Flyby, Cassini,* and *Mars Observer* will place still further demands upon current telescopes. In addition, growing interest in investigating star-formation regions and young stellar objects drives astronomers toward infrared imaging and spectroscopy at planetary-system scales of a few astronomical units. Only very large telescopes in the 6- to 10-meter class at sites with excellent infrared transparency and stability can achieve the required spatial resolution in the thermal infrared for the nearest active star-forming regions. These considerations argue that NASA should plan to provide access for planetary astronomers to this new generation of more powerful optical/infrared telescopes.

Although the Planetary Astronomy Committee does not recommend that NASA commit to the full construction and operating costs of a 6- to 10-meter optical/infrared telescope, we do feel that the Solar System Exploration Division must begin to explore ways in which access to such telescopes can be provided to planetary astronomers in the 1990s. At this time, several consortia of Federal and private agencies and universities are being formed to plan and construct such instruments. For example, the National Optical Astronomy Observatories are developing plans for two 8-meter telescopes, one to be built at Mauna Kea in Hawaii and one to be built at an excellent southern hemisphere site. We recommend that NASA initiate discussions with the National Optical Astronomy Observatories or other interested parties with the intention of developing a partnership that will ensure that these facilities will be used to support planetary astronomy in the mid-1990s and beyond.

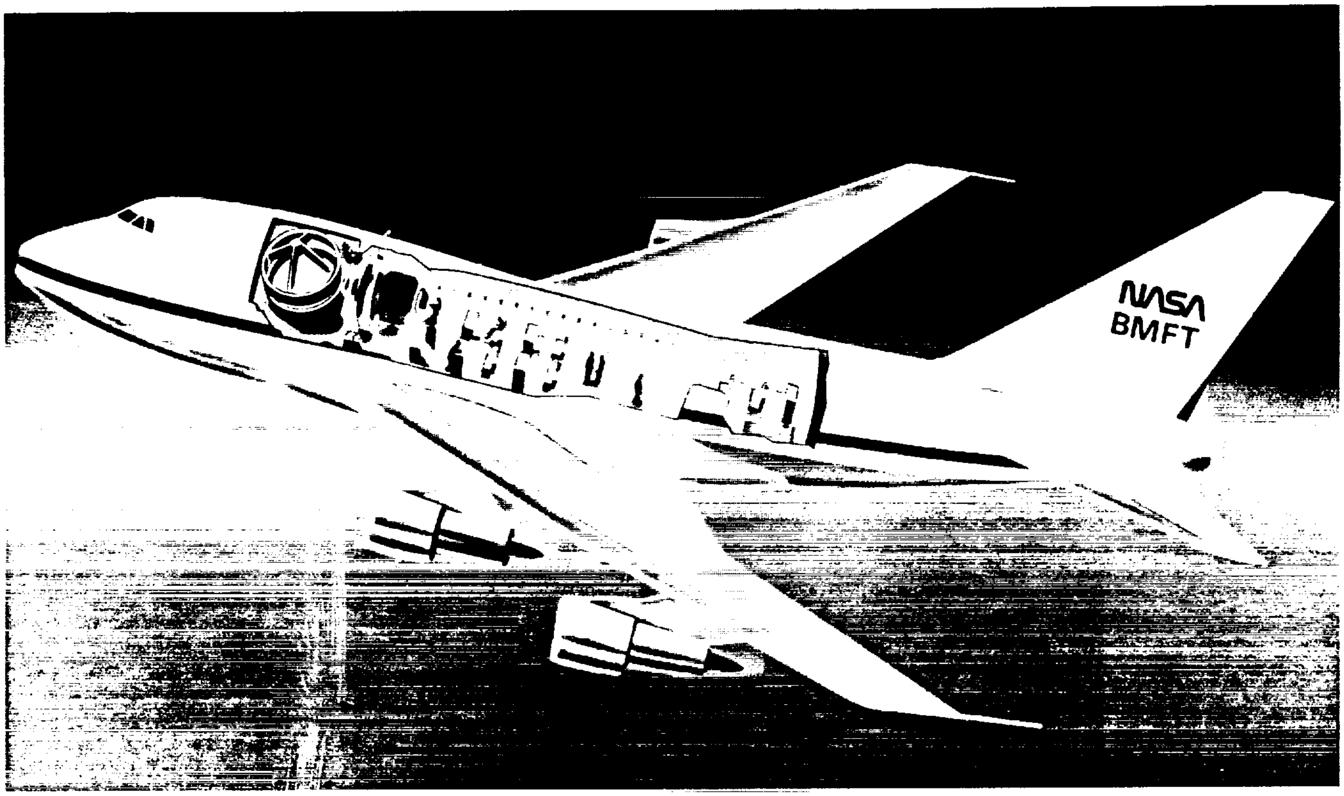
The **Comet Rendezvous Asteroid Flyby** *mission, shown here on a 50,000-kilometer excursion down the tail of a comet.*

New Instrumentation for Ground-Based Telescopes

The technology of astronomical instrumentation, both in the visible and infrared spectral regions, is moving forward at an extremely rapid pace. Not only are new techniques, such as speckle interferometry, heterodyne detection, and high-speed photometry, advancing our capabilities in data acquisition, but new array detectors with increased sensitivity and expanded wavelength coverage are also vastly increasing the capabilities of all telescopes. The community of planetary astronomers is anxious to move ahead to develop front-line instrumentation for use on existing telescopes. In a 1986 survey of principal investigators supported through the NASA Planetary Astronomy Program, most respondents urged the construction of new instrumentation to provide for two-dimensional imagery in the visible and infrared, and the construction of infrared spectrometers with improved sensitivity and throughput for the measurement of extremely faint sources.

Major steps forward in detector technology promise a tenfold improvement in the sensitivity of infrared sensors, coupled with enormous gains through application of one- and two-dimensional detector arrays. These new detector arrays, when applied to spectroscopic instruments, promise overall gains of factors of 100 to 100,000 in the near- and mid-infrared, where so much information on planetary atmospheres and surfaces and on regions of star formation lies. An improvement in system detectivity by a factor of 100 is

The proposed SOFIA would use a 3-meter class telescope in a Boeing 747 airplane to observe planetary sources with good angular resolution at infrared wavelengths inaccessible from the ground.



equivalent to increasing the diameter of a telescope by a factor of 10.

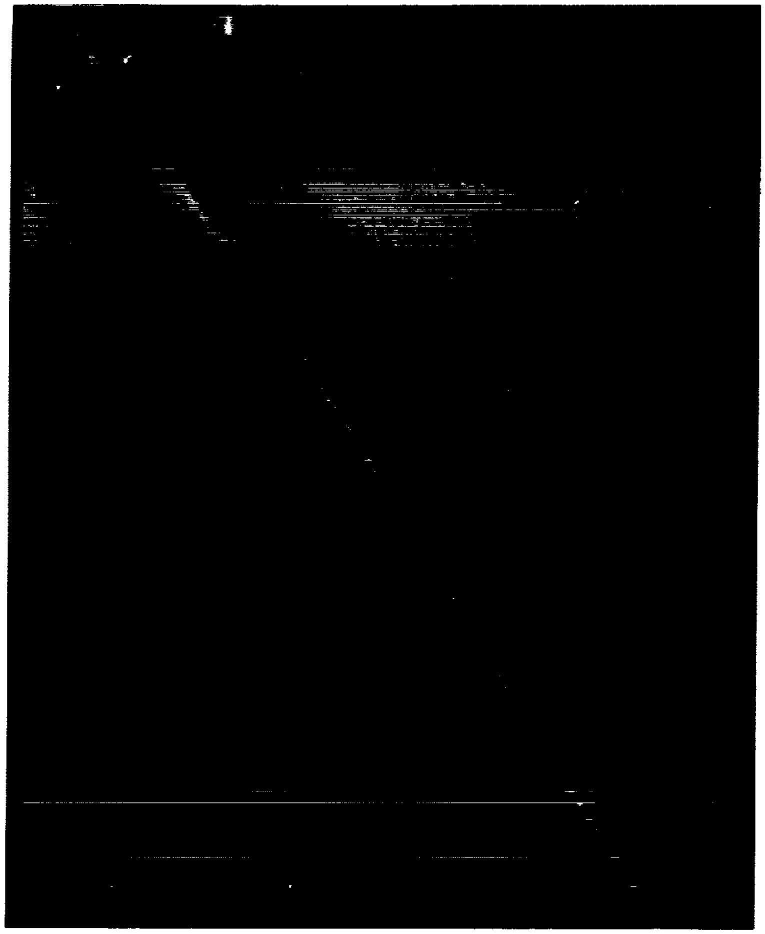
These technological advances must be implemented in astronomical instruments for use by planetary scientists on the ground-based and airborne telescopes presently available or projected for the near future.

New Airborne Telescope

The great success of the Kuiper Airborne Observatory since it became operational in 1975 has prompted the development of a plan for a larger airborne telescope. At the NASA Ames Research Center, a plan for the Stratospheric Observatory for Infrared Astronomy (SOFIA) is under study. A 3-meter class telescope in a Boeing 747 aircraft is the concept for the initial design. Although the stabilization and tracking will be modeled after similar successful systems on the KAO, improvements in a number of the operating parameters are planned. Of importance are the expected improvement in telescope emissivity, the modest improvement in the image size due to seeing in the telescope, and the longer time available at maximum altitude.

Several programs in planetary science have already been identified in connection with the development of the SOFIA concept. Spectroscopy in the region 1 to 8 micrometers for the detection of diagnostic atmospheric and surface spectral features, far infrared and submillimeter spectroscopy for the study of molecular hydrogen and the hydrogen-deuterium molecule in the atmospheres of Jupiter and Saturn, observations of planetary atmospheres and rings by occultation techniques, and more sensitive observations of comets have all been suggested. In addition, far infrared photometry of pre-planetary

Haze layers in Titan's nitrogen and methane atmosphere.



circumstellar disks would contribute significantly to the developing studies of these planet-related phenomena. The Committee recognizes the importance of SOFIA for planetary investigations and strongly endorses NASA's efforts to secure an early start on its development.

New Instrumentation for Airborne Telescopes

NASA's Airborne Science Program supports principal investigator instruments for use on the KAO. In recent years, support for flights of this observatory has been less than that needed for a vigorous program that would take full advantage of the power of the facility to contribute to astrophysics and planetary astronomy.

In addition to increased support for flights of the KAO, a strong program for the development of new instrumentation incorporating the newest array detectors and other techniques is needed. Photometers, array cameras, and multiplex spectrometers of various types must be kept current and available through principal investigator instrument development grants.

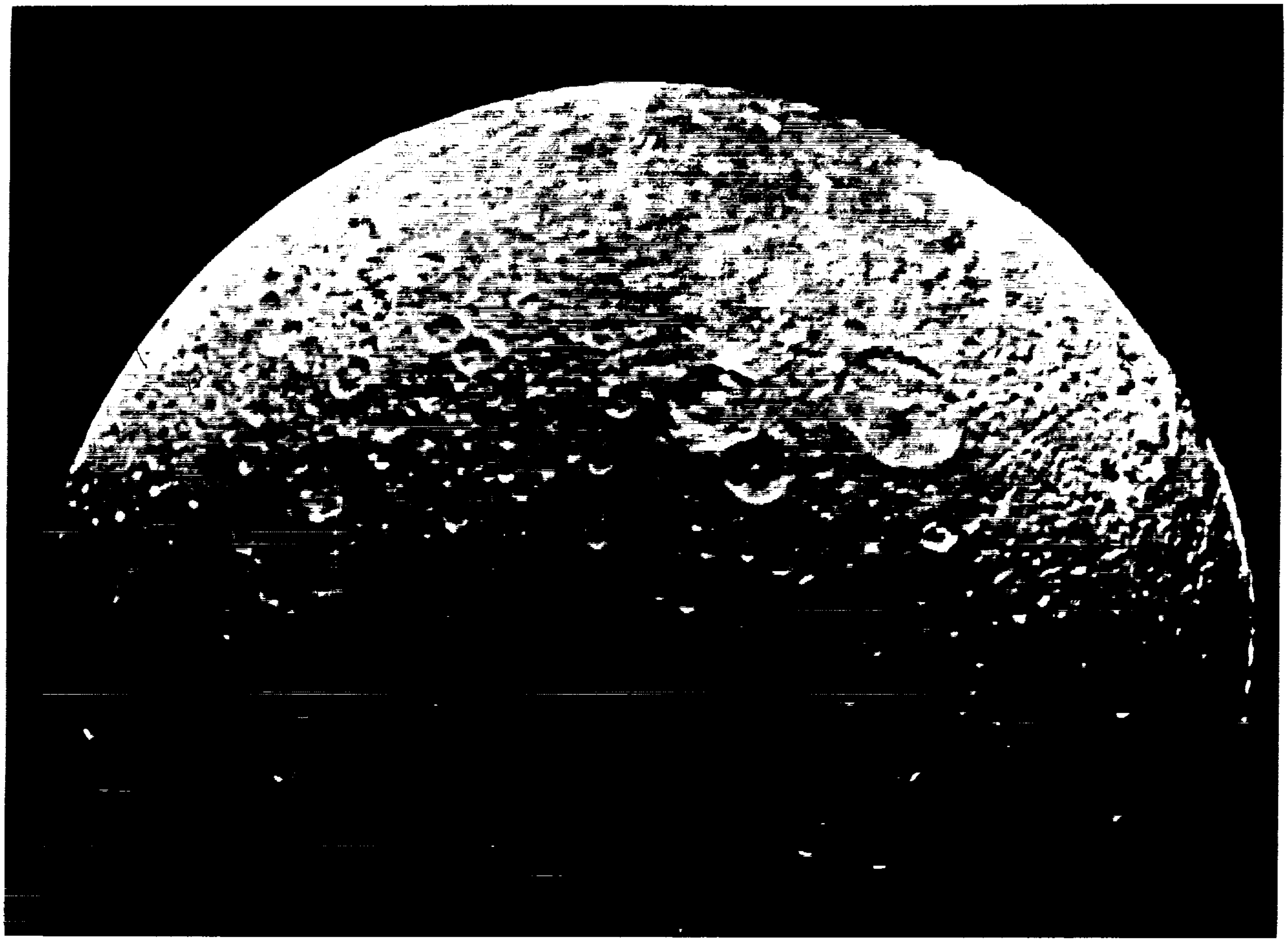
For SOFIA, modern instrumentation is again the key to scientific work on the cutting edge. Planetary astronomers would use the most sensitive array cameras, photometers, and spectrometers throughout the wavelength region available to the facility. Another issue concerns the seeing in the SOFIA telescope, which is influenced by aerodynamic effects. The design anticipates achieving 3-arcsec images, an improvement over the KAO, but far inferior to that in telescopes at the better ground-based sites. Money spent in improving the SOFIA seeing to, perhaps, 1 arcsec or better would very substantially increase the power of the telescope to do certain kinds of planetary observations. The degree of this improvement would vary with wavelength region and the kind of observations being made, but both planetary and astrophysical users of SOFIA would benefit significantly, particularly at the shorter wavelengths for which the facility will be used. The Committee recommends that an effort be made to design the SOFIA telescope and its aircraft interface in such as way as to produce seeing that is nominally 1 arcsec or better. The funds for this development could be provided by the Solar System Exploration Division.

Upgrades of Arecibo and Goldstone

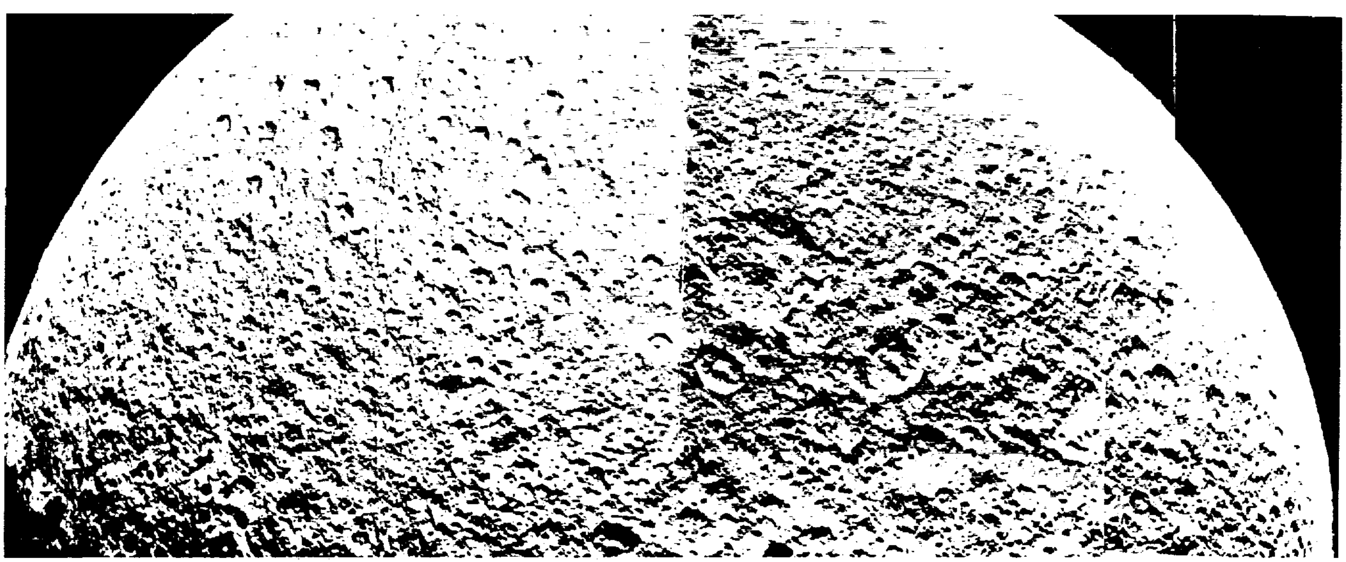
A recent proposal for upgrading the Arecibo radar telescope calls for: (1) constructing a ground screen around the periphery of the dish, (2) replacing the line feeds with much more efficient, offset Gregorian subreflectors, (3) doubling the output power of the 13-centimeter transmitter, and (4) installing a fine-guidance pointing system. These upgrades, most of which would be funded by the NSF as part of its continuing responsibility for the National Astronomy and Ionosphere Center, would increase the instrument's radar sensitivity by a factor of 20, more than doubling its range and reducing by nearly an order of magnitude the diameter of the smallest object detectable at any given distance. The quality, in terms of signal-to-noise ratio and/or spatial resolution, of all measurements performed routinely today would jump by more than an order of magnitude.

The impact of an upgraded Arecibo on planetary science would be fundamental and far-reaching, especially for studies of small bodies and planetary satellites. During its first decade of operation, the instrument would provide 300-meter-resolution images of about 30 near-Earth asteroids and 30-kilometer-resolution images of up to 100 main-belt asteroids. It also could furnish unique information about near-surface bulk density, structure on the scale of centimeters to meters, and metal abundance for nearly all the asteroids numbered up to 100, for 20 percent of all 4,000 currently numbered main-belt asteroids, and for about 50 percent of the numbered near-Earth asteroids.

Currently, Arecibo can barely skim the inner edge of the main asteroid belt; an upgraded instrument would have access to asteroids throughout the belt. Most newly discovered near-Earth asteroids entering Arecibo's declination window would be detectable, and just a few minutes worth of echoes could guarantee optical recovery of the asteroid during subsequent apparitions. By preventing the loss of Earth-approachers, radar would help enlarge the pool of candidates for space missions. Similarly, short-period comets, which generally lie at the edge of the current detectability window, would become easy targets, letting us determine their nuclear characteristics and check for the presence of large-particle clouds.



A collection of solar system satellites that would be detectable by an upgraded Arecibo. Above, Saturn's moon Dione.



Rhea, another Saturnian satellite.

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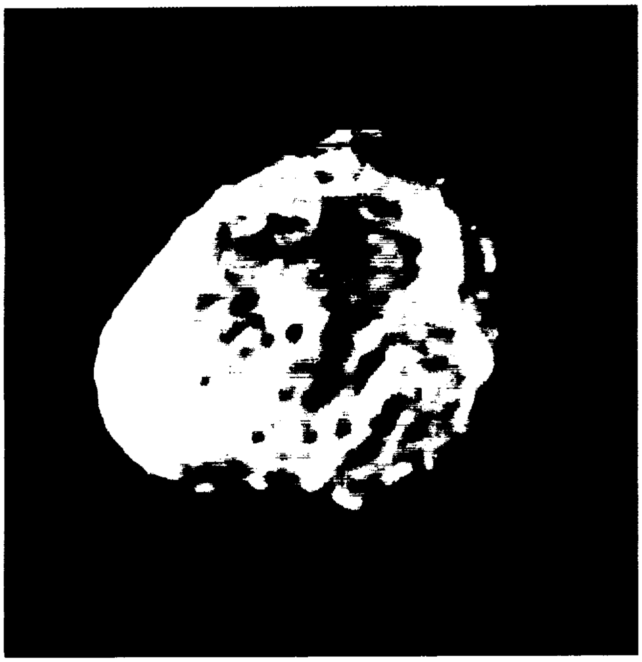
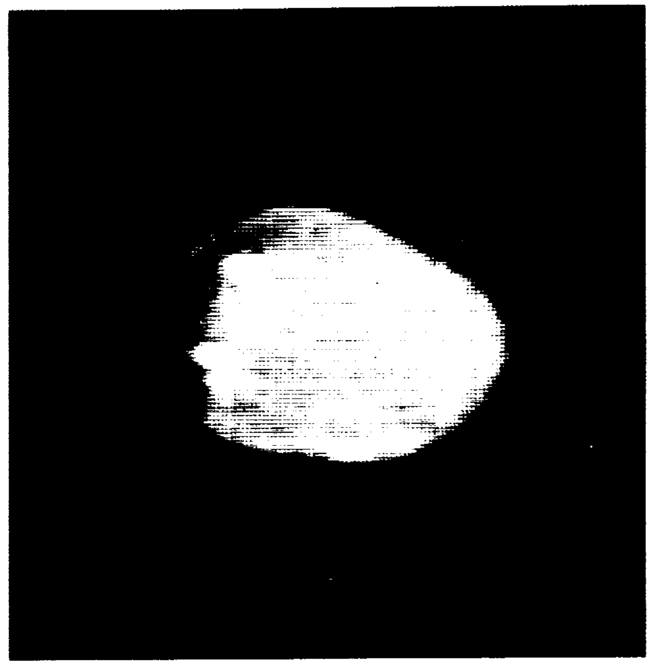
Hyperion, also a member of the Saturn system.



Amalthea, a satellite of Jupiter.



Radar investigations of natural satellites would reap enormous benefits, especially for the study of Io and Titan, whose near-surface physical properties and centimeter-to-kilometer structural properties would be readily discernible. The regoliths of the icy Galilean satellites could be probed to depths of 100 meters or more and studied on a global scale, and the near-subsurface rock populations on Phobos and Deimos could also be studied. Iapetus would be detectable, and radar measurements could elucidate the subsurface character of the disparate hemispheres of this unusual object. Rhea and Amalthea would probably be detectable, and such smaller satellites as Dione and Hyperion would lie near Arecibo's limits, where Io and Titan are now.

Goldstone's 65-meter antenna has been enlarged to 70 meters in preparation for *Voyager's* 1989 flyby of Neptune, doubling the radar's sensitivity. An additional, three-fold improvement appears to be possible by increasing the output power through a redesign of the transmitter.

Discovery of Other Planetary Systems: Doppler Spectroscopy

Doppler spectroscopy, which measures extremely small motions of stars in response to unseen orbiting companions, is proving to be a powerful technique for the detection of other planetary systems. The level of precision already achieved (10 meters per second) opens a large and important segment of the phase space that might be occupied by other planetary systems; namely, those consisting of compact planetary systems accompanying low-mass stars.

More than half of all known stars in our galaxy are main-sequence dwarfs of spectral types K and M, with masses between 0.5 and 0.1 that of the Sun. If these stars have planetary systems, and if these systems include giant planets that formed in the temperature regime (100 to 200 Kelvins) occupied by Jupiter and Saturn in our own system, then these giant planets will be found relatively near such low-mass stars (typically near 2 astronomical units, with orbital periods of a few years). The reflex motion of a star of less than 0.5 solar masses due to a "Jupiter" at 2 astronomical units distance is measurable at a precision of 10 meters per second.

Thus, present doppler spectroscopic observing programs, if extended to a sample of 100 or more M and K dwarfs and continued for a decade, can apparently provide a definitive determination of whether such stars have compact planetary systems that include objects of Jovian mass. Such a study constitutes an essential part of the systematic search for other planetary systems. The Committee recommends that the Solar System Exploration Division provide leadership and support to ensure that this survey is carried out in conjunction with other more technically challenging (and more costly) techniques needed to extend this search.

Discovery of Other Planetary Systems: Ground-Based Astrometry

Astrometric searches for other planetary systems complement those carried out by doppler spectroscopy, in that they are more sensitive to extended rather than compact planetary systems. As discussed earlier, current ground-based astrometry at a precision of 1 to 3 milliarcsec is capable of detecting a Jovian-mass planet only for the nearest few dozen stars, and only if the stellar mass is less than about 0.3 solar masses. However, the expected gains in astrometric precision that can be achieved with a modern dedicated astrometric telescope at a site with excellent seeing should permit studies with precisions as good as 500 microarcsec, thereby bringing a wider variety of potential planetary systems within range.

Ground-based astrometry with a dedicated telescope at an excellent site will effectively complement the doppler spectroscopic method and will bring within our reach another significant segment of planetary-system phase space. Such a telescope will be capable of detecting the reflex astrometric motion of K and M main-sequence dwarf stars produced by planets of Jovian or Saturnian masses in orbits with radii greater than about 2 or 3 astronomical units. The periods for such orbital motion are typically in the range of 5 to 10 years, so an extended survey is required. At least 100 stars are within range of such an astrometric telescope with modest aperture (1 to 2 meters).

The combination of ground-based astrometry with ground-based doppler spectrocopy will yield a definitive survey of a statistically significant set of K and M stars, with detection capability for Jovian-type planets over a wide range of possible orbital radii. In addition, astrometric telescopes can extend this search to a smaller group of the closest stars of solar type (classes F and G). We recommend that NASA vigorously advocate the development, perhaps jointly with the National Science Foundation, of a dedicated astrometric telescope of 1- to 2-meter aperture at the best possible site to extend the search for other planetary systems beyond the limited capability of current astrometric and doppler spectroscopy programs. Such an instrument will provide important statistical results and will serve as a testbed for future astrometric instruments in space, as well as offer a good prospect of discovering one or more other planetary systems. Beginning the search now from the ground is both timely and prudent. The results promise to be exciting, and the experience will be invaluable as a precursor to the more advanced orbital facilities to follow.

Summary Recommendations for Ground-Based and Airborne Planetary Astronomy

Compared with space missions to solar system targets, the time scale of planetary astronomy investigations is extremely short; therefore, projecting specific needs for more than the next few years is not possible. However, reestablishing a vigorous effort in planetary astronomy is essential to the progress of planetary science and the definition of productive spacecraft missions. We have defined a short-term program and have indicated what we see as fruitful areas for planetary astronomy in the longer term.

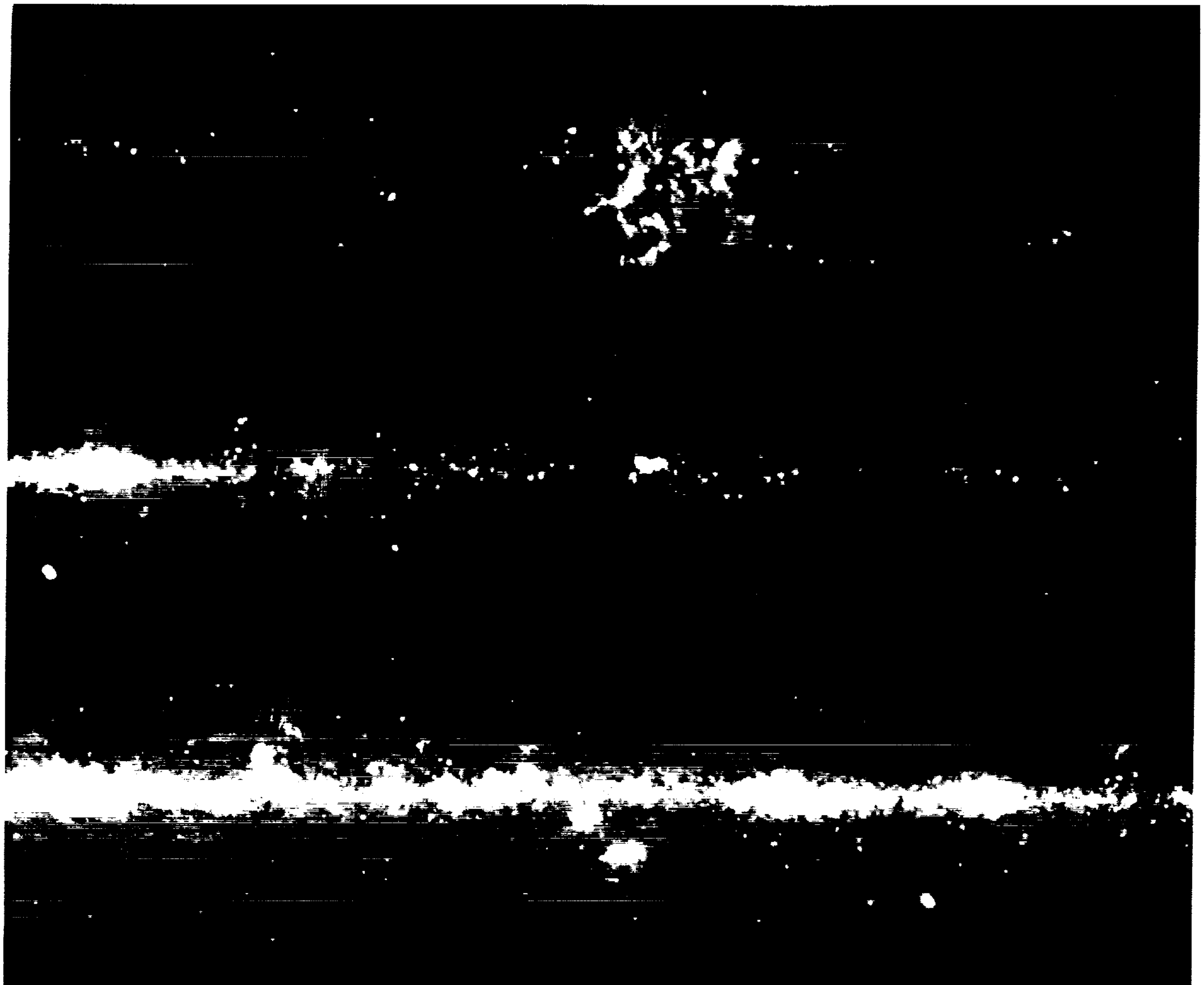
Short-Term Plan

- Strengthen grants program immediately.
- Make Arecibo upgrades.
- Support SOFIA for planetary observations.
- Encourage continuation and expansion of search for other planetary systems by doppler spectroscopy.
- Initiate studies with the National Science Foundation on a dedicated astrometric telescope for the detection of other planetary systems.
- Provide support for such instrumentation as:
    - High-resolution infrared spectrometer.
    - Large format optical charge-coupled device (2000 X 5000) with coronagraph.
    - Faint-object infrared spectrometer.
    - Set of portable, high-speed charge-coupled devices for occultations.
    - Near-infrared array camera with coronagraph.
    - New devices based on 10-micrometer array technology.

Long-Term Plan

- Remain on cutting edge of instrumentation for ground-based and airborne telescopes.
- Study extrasolar planetary material by all means available.
- Provide observational support for deep-space missions, and follow up on important discoveries.
- Apply technology to improve seeing (image quality).
- Establish close involvement in National Optical Astronomy Observatories and other major telescope initiatives.

This IRAS image shows a 90-degree section along the plane of our Galaxy, with the Galactic Center in the top right. Each frame in this mosaic shows about 40 degrees and overlaps adjacent frames. Emission from warm material is blue, from cooler material it is green, and from the coldest material it is red.



Earth-Orbital Planetary Astronomy

Two decades of research and discoveries using small astrophysical observatories, such as the *International Ultraviolet Explorer (IUE)* and the *Infrared Astronomical Satellite (IRAS)*, have demonstrated the utility of Earth-orbital systems for exploring the solar system. We believe that future prospects for this activity are both remarkable and exciting, as versatile and immensely powerful space observatories are planned, both at home and abroad, for launch or development in the near future. In addition, the Space Shuttle can become the host to small, but highly specialized, instrumentation designed for solar system research, and a decade hence, new opportunities can be expected in the use of Space Station *Freedom*.

The planetary science community has recently become much more aware of the potential of Earth-orbital planetary astronomy as a result of activities surrounding the development of the *Hubble Space Telescope* and the *Space Infrared Telescope Facility*. Planetary studies conducted in Earth orbit can extend the search for answers well beyond the boundaries of the solar system to planetary systems elsewhere in the Galaxy. Closer to home, Earth-orbital planetary astronomy can provide invaluable information that will enhance the scientific productivity of major planetary flight missions. In the longer term, scientific information, inaccessible in any other way, will be obtained to assist in the planning, design, and priorities for future instrumentation and deep space missions.

Within NASA's Office of Space Science and Applications, the primary responsibility for Earth-orbiting astronomical facilities lies with the Astrophysics Division, not with the Solar System Exploration Division. As a result, certain programmatic problems must be solved if Earth-orbital planetary astronomy is to achieve its proper role in planetary science. Earth-orbital planetary astronomy, productive as it has been, is not well integrated into the scientific programs of the Office of Space Science and Applications, and it has been largely disregarded in the Solar System Exploration Division.

Summary of Achievements

Remarkable results in planetary astronomy have been achieved utilizing Earth-orbital telescopes even though they were not optimized for studies of the solar system. In the case of the early *Orbiting Astronomical Observatories* and their successor, the *IUE*, information has been obtained on global stratospheric chemistry and dynamical processes in the outer planets, and ultraviolet airglow emissions on Venus have been used to trace mixing processes high in that planet's atmosphere. Lyman-alpha studies on the outer planets have yielded information about large-scale turbulent mixing in their upper atmospheres and have traced the atmospheres' interaction with energetic particles precipitated from radiation belts trapped by planetary magnetic fields.

Earth-orbital studies of the Io torus have provided a view of the structure and the physical conditions in this complex dynamical system that complements insight obtained from the ground and from planetary spacecraft. Wide regions of sulfur dioxide absorption have been mapped throughout the equatorial regions on Io's surface. Such data supplement the view from *Voyager* and have helped shape the interpretation of *Voyager* data.

The study of comets took a forward leap when observations from the *Orbiting Astronomical* and *Orbiting Geophysical Observatories* revealed comets' enormous Lyman-alpha comae. Since then, the *IUE* has been prolific in producing new insights into the physics and chemistry of these objects. The *IUE* discovery of S_2 in Comet IRAS-Araki-Alcock, which itself was discovered by *IRAS*, demonstrated the combined power of high spatial resolution and ultraviolet spectroscopy from Earth orbit. In the infrared region, the *Infrared Astronomical Satellite* results have helped to open a new view of a solar system criss-crossed with trails of disintegrating comets and asteroid dust, perhaps due to past collisions. In addition, the *IRAS* has pointed the way to extending planetary science beyond the borders of our solar system by detecting disks of particles around nearby stars.

These discoveries presage the future productivity of immensely more powerful astrophysical observatories, which soon will be in orbit.

Significance for NASA's Solar System Exploration Program

Certain classes of observations require extended coverage in time, a global view of the phenomenon being studied, and freedom from the obscuration and distortion of Earth's atmosphere. Such investigations must be performed from Earth orbit. Examples abound: studies of dynamical transport processes in the atmospheres of Venus, Mars, and Jupiter; episodic activity in the Jovian magnetosphere and on Io; and unpredictable activity in cometary atmospheres.

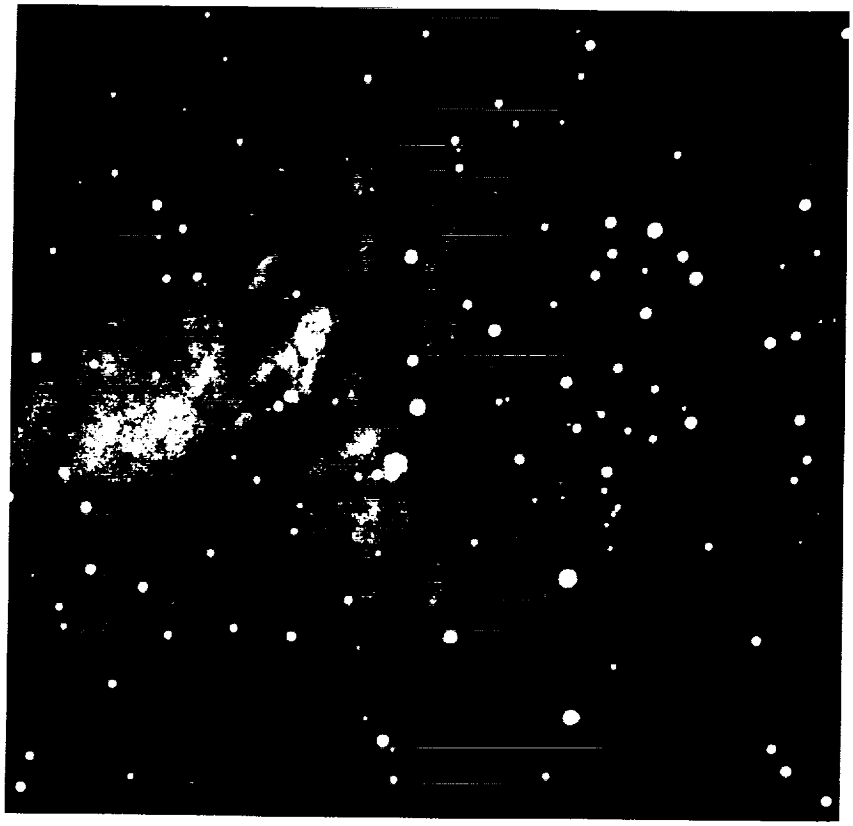
Observatories in Earth orbit are sufficiently distant from the object being studied to capture the global context of a phenomenon. Recent examples can be found in the coverage of Comet Halley from the *IUE* at the time of the *Giotto* and *VEGA* flybys. The spacecraft mass spectrometers sampled the elemental and molecular composition in a specific region at a particular time, but the remote-sensing spectrometers in Earth orbit, on the Kuiper Airborne Observatory, and on the ground followed some of the changing abundances throughout the coma and also bridged the time between encounters.

An aggressive program in Earth-orbital planetary astronomy should be an essential component of NASA's Solar System Exploration Program. Such a program will enhance the scientific results of future deep space missions, help provide the scientific basis for planning future missions, and generate data, unobtainable in any other way, that are important to reaching the goals of the Solar System Exploration Program.

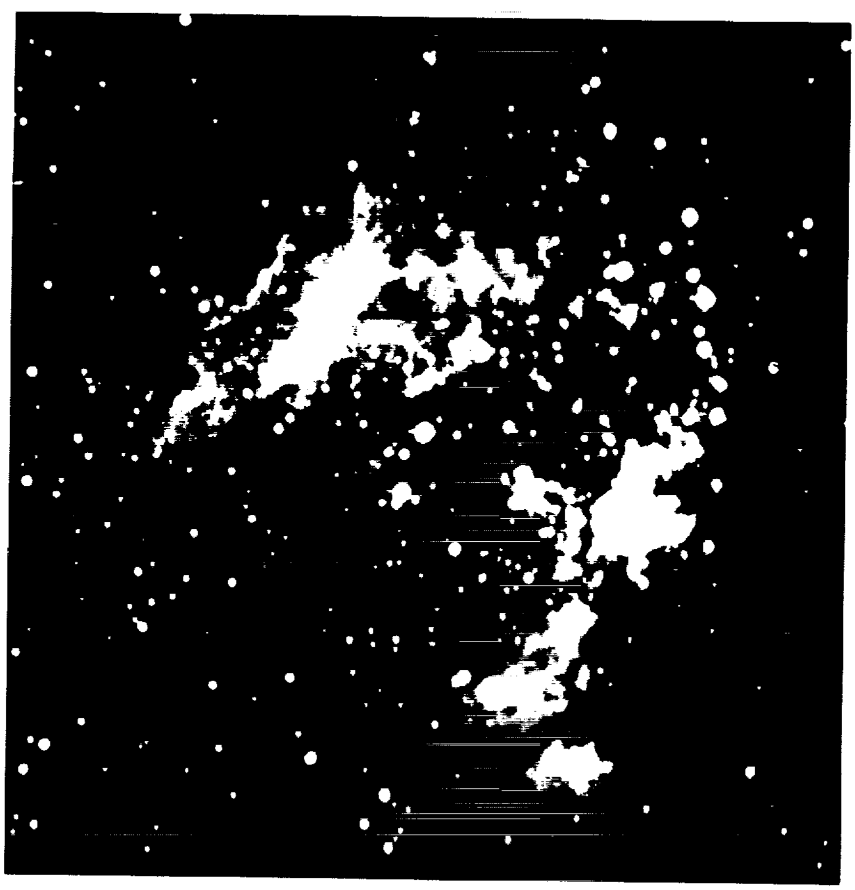
Earth-Orbital Astrophysical Observatories

Planetary observations place special requirements upon astronomical telescopes, on Earth or in space. Traditionally, astronomical observatories have been conceived, developed, and operated by scientists investigating stars and galaxies in deep space, rather than the bodies in our own planetary system. Recent gains in close-up knowledge of the planets, combined with the remarkable performance expected of future telescopes in Earth orbit, prompt a recognition of the special measurement requirements of planetary science. First among these is the need to acquire and track moving planetary features accurately. The requirements for excellent scattered light rejection and unusual instrument performance, such as very high spectral resolution, are important, although not unique to planetary observations.

Significant potential for planetary science lies in the utilization of the Great Observatories being developed by NASA, and of certain facilities being developed by the European Space Agency. Although these facilities do not provide the complete capability that is needed for planetary studies, the capability that could be available is truly remarkable.



Visible and infrared images of the star-forming region M 17. The top image is in visible light, while the bottom is a composite composed of infrared images that penetrate the thick clouds of dust to reveal newly formed stars.



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The Astrometric Telescope Facility

The *Astrometric Telescope Facility* (ATF) system is composed of six subsystems (Optics, Structure and Mechanisms, Thermal Control, Command and Data, Pointing and Control, and Power and Harness) plus the Focal Plane Instrument. These elements are integrated into a system designed to meet the mission requirements and the basic science requirement to measure relative star motion with an accuracy of 10 microarcsec.

Figure 5 shows the overall layout of the ATF. The telescope is designed as an F/13 system with a 1.25-meter-diameter primary mirror. A bar across the front of the telescope tube supports the position detector and the relay optics that direct the beam to the side of the tube and refocus and magnify the image at the Focal Plane Instrument. Also shown on the figure are the sunshade and protective cover. The overall length of the telescope is about 22 meters, including the sunshade. The telescope is wrapped with a thermal blanket to minimize temperature changes associated with varying solar and Earth-illumination conditions. Overall diameter of the assembly, including the blanket, is approximately 1.85 meters. The telescope is held at its center of gravity in the ATF Vibration Isolation/Vernier Pointing System which is, in turn, attached to the Space Station *Freedom* coarse pointing system. The Vibration Isolation/Vernier Pointing System isolates the telescope from *Freedom's* vibrations and provides a second level of pointing to reach the mission pointing accuracy requirement of 1 arcsec (coarse pointing system capability is limited to approximately 30 arcsec). Also included in this assembly is a mechanism to rotate the telescope 180° in either direction about the optical axis. The mass of the ATF mounted to the coarse pointing system is 5,100 kilograms.

Redundancy has been implemented by providing two independent strings of electronics, cross-strapped only at the three non-redundant units, the Focal Plane Instrument, visible imager, and gyroscope. Making the Focal Plane Instrument redundant appears impractical, and the instrument does contain important elements of redundancy. The gyros are internally redundant. The interface with *Freedom* has been kept to a standard data and power interface. The maximum data rate is 1.75 Mbps, and power levels are 1,400 W average, 2,500 W maximum.

The system is designed to be fail-safe and single-fault tolerant. It is assumed that the coarse pointing system will include safety features to prevent telescope pointing that could physically damage the telescope, *Freedom,* or other science payload hardware. Based on this assumption, the potential critical conditions for ATF are pointing of the telescope into the Sun, exposure to high levels of contamination, or significant over- or under-voltage conditions. An aperture cover will protect against improper pointing or contamination and it is designed to close automatically, without need of external power, if power to ATF is lost or critical mispointing is detected by onboard Sun sensors. The ATF system is protected from anomalous voltage conditions by the power subsystem electronics. Noncritical failures have been accommodated by the redundancy approach described previously.

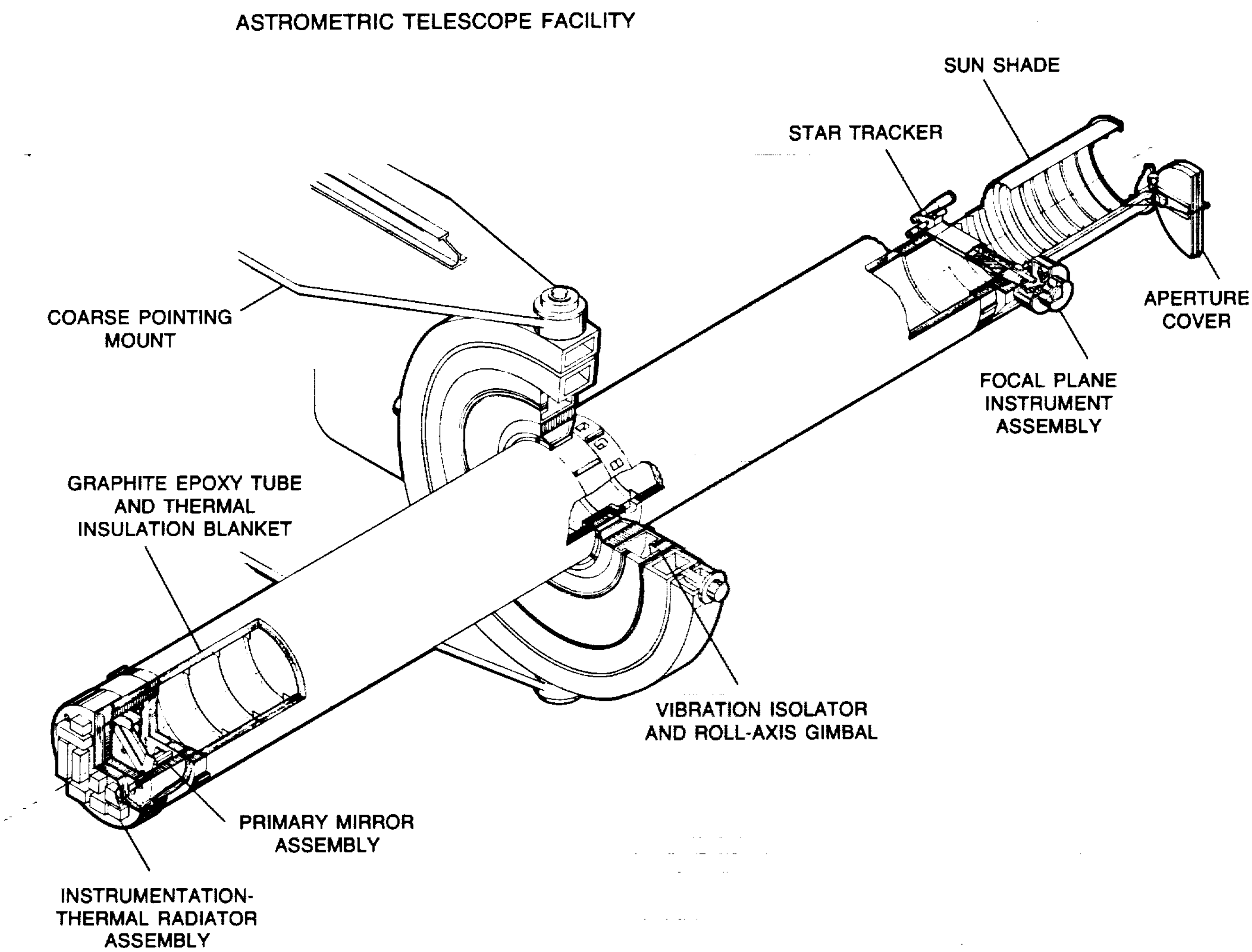
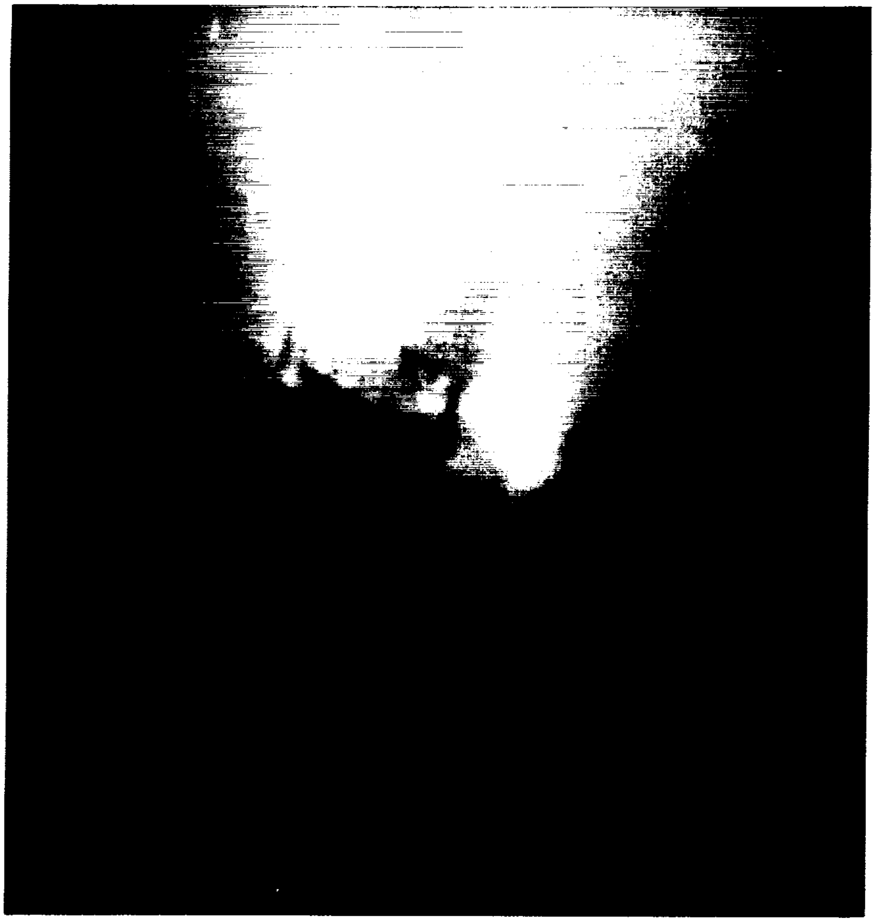

ASTROMETRIC TELESCOPE FACILITY
SUN SHADE
STAR TRACKER
APERTURE COVER
COARSE POINTING MOUNT
FOCAL PLANE INSTRUMENT ASSEMBLY
GRAPHITE EPOXY TUBE AND THERMAL INSULATION BLANKET
VIBRATION ISOLATOR AND ROLL-AXIS GIMBAL
PRIMARY MIRROR ASSEMBLY
INSTRUMENTATION-THERMAL RADIATOR ASSEMBLY

Figure 5

The nucleus of Halley's Comet, as seen from the European Space Agency's Giotto *spacecraft.*



The Hubble Space Telescope

The *Hubble Space Telescope,* first of the Great Observatories, offers tremendous improvement in spatial definition and sensitivity over any previous orbiting telescope; it will have 50 times the light grasp and 30 times the spatial resolution of earlier Earth-orbital observatories. The *Hubble Space Telescope* instruments include: high-resolution, relatively wide field imaging cameras operating in the visible and ultraviolet spectral regions; spectrographs capable of simultaneously making observations with the highest spatial and spectral resolution; and a high-speed photometric system suitable for recording rapidly variable phenomena with great discrimination against background light. This facility should play a broad and significant role in future planetary science, and it has potential applications to essentially all known planetary phenomena. The planetary community has participated in the justification of the facility because of its evident utility for planetary studies. But to deliver on that potential, the *Hubble Space Telescope* must be capable of performance that is not yet assured.

If a "first law of telescopes" were defined, it would be that the uncertainty in pointing must be small compared with the resolution footprint on the sky; otherwise, the spatial resolving power is wasted. For the *Hubble Space Telescope,* a diffraction-limited telescope for wavelengths longer than 400 nanometers, the pointing precision should be about 20 milliarcsec. This corresponds to about 60 kilometers at the distance of Jupiter and to the rotational displacement of a cloud feature at the center of the planet's disk in 5 seconds. Since 5 seconds is a short time for many observations, precise pointing and tracking are essential. Planetary targets appear to move against the background of stars, because of the contributions of heliocentric orbital motion, planetocentric motions such as rotation and satellite orbiting, and horizontal parallax. A complex combination of advanced planning and technical performance is required for target acquisition and tracking. Similarly, the system must provide accurate post-data-acquisition knowledge of the observational pointing history if the data are to be successfully utilized. Unfortunately, these challenges, although technically feasible and originally specified in project requirements, have not yet been met for the *Hubble Space Telescope,* and are not now planned to be met by the time of launch. We recommend that higher priority be given to solving these problems, to help the planetary community make practical plans for utilizing the *Hubble Space Telescope.*

The currently planned set of instruments does not cover the full range of applications that could be addressed by the *Hubble Space Telescope* and that are envisioned by the astronomical community. The technology built into some of the instruments has already been surpassed by advances since the project began in 1978. As a result, development is under way in the Astrophysics Division of a second generation of instruments for the telescope, to be included in the payload sometime after the present system has been placed in orbit. These instruments include a new wide field camera and a near-infrared system that can simultaneously image a target as it analyzes the target's spectrum. The ongoing development of such instruments offers the opportunity to incorporate capabilities that are advantageous to planetary astronomy. The Solar System Exploration Division must involve itself in, and maintain a good liaison with, this instrument-definition activity.

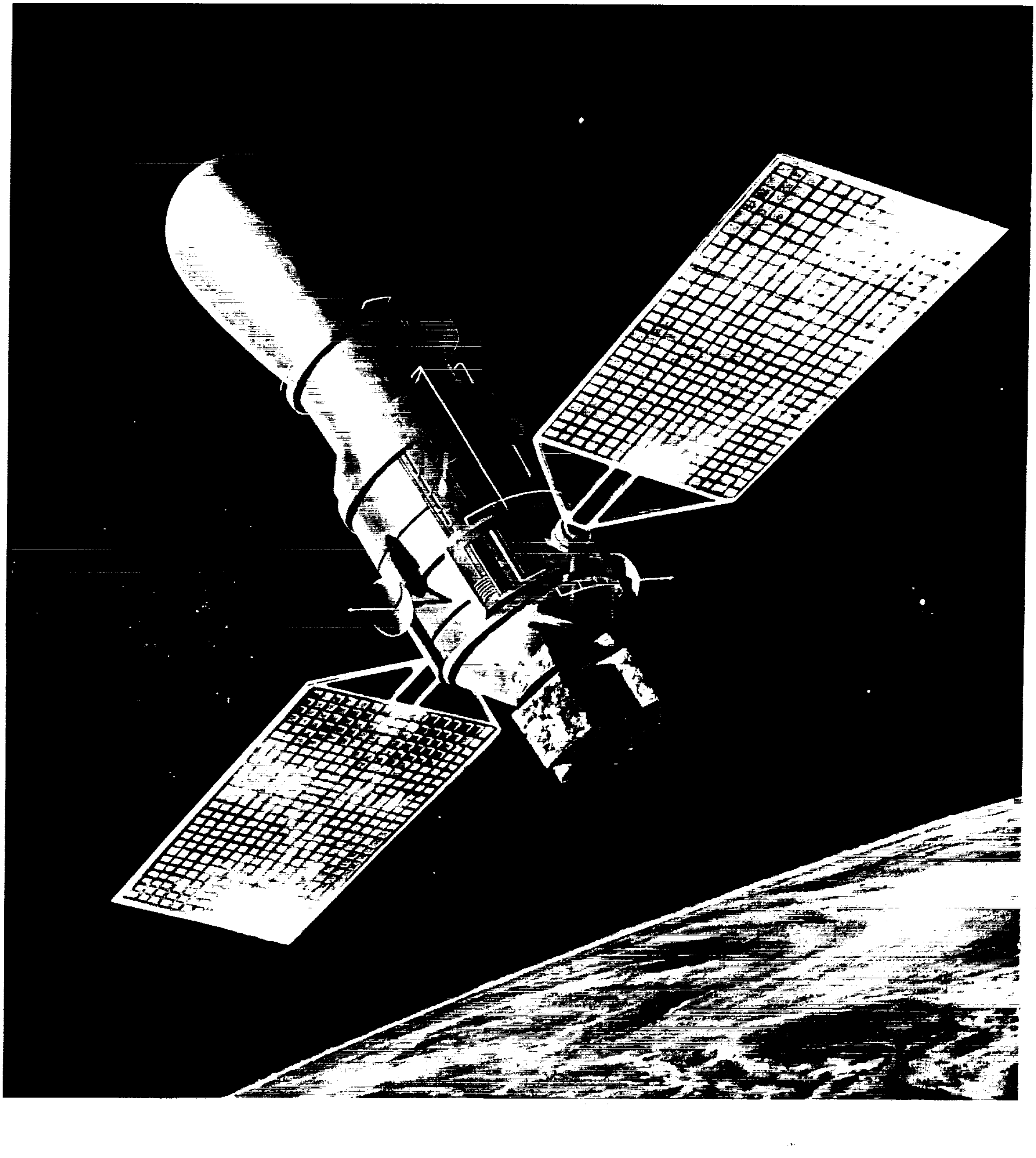
The Space Infrared Telescope Facility (SIRTF)

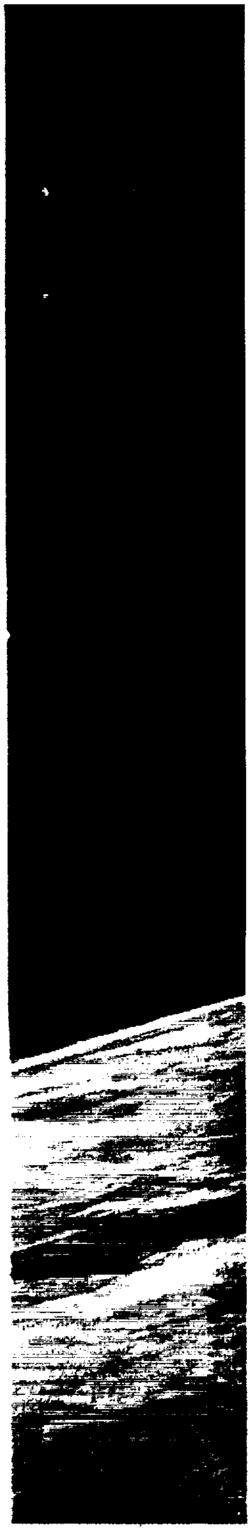
Planetary science has long been identified as an important scientific area for *SIRTF,* and this view has been reinforced by many of the interesting results obtained from the *Infrared Astronomical Satellite.* Therefore, even though planetary scientists have not been well represented numerically on the *SIRTF* science teams until recently, the design of the system has been motivated in part by the needs of this community.

SIRTF offers the following capabilities:

- High sensitivity in the thermal infrared at low to moderate spectral resolution
- Near simultaneity of observations at all infrared wavelengths covered
- Freedom from atmospheric absorption
- Measurement of low surface brightness emission
- Synoptic observations over time periods of months to years
- Precise photometric measurements.

The Space Infrared Telescope Facility *will span the infrared part of the spectrum with tremendous sensitivity.*





When applied to planetary science, the importance of *SIRTF* (with currently planned instrumentation) lies in its greatly increased sensitivity over ground-based infrared telescopes, its broad spectral coverage, its capacity to image in the infrared, and its currently planned pointing and tracking capability. As a benchmark, we note that *SIRTF* will easily be able to make high signal-to-noise, moderate spectral resolution measurements in the thermal infrared of the nucleus of a comet like Halley at the position of Jupiter's orbit. Thus, inferences about the global properties (size, temperature, albedo) of many such objects are possible before their surfaces become obscured by the development of their active, dusty atmospheres.

SIRTF will have unique application to almost every area of planetary science: studies of planetary atmospheres, satellite surfaces, asteroids, cometary nuclei, and extrasolar planetary material.

Substellar objects of masses greater than a few Jupiter masses (brown dwarfs or infrared dwarfs) associated with nearby low-luminosity stars should be detectable with *SIRTF's* 20-micrometer camera if the objects are more than about 10 arcsec distance from the primary star. The 60 closest low-luminosity stars can be studied for such companions out to orbital radii of about 750 astronomical units in less than 50 hours of observing, and this program is expected to have a high scientific priority for *SIRTF*. Techniques of resolution boosting to optimize the detection of planetary-mass objects are being, and should continue to be, explored.

Extended distributions of matter around other stars, such as the disks around Vega and Beta Pictoris, can be studied in detail by *SIRTF's* diffraction-limited imaging capability at thermal wavelengths; *SIRTF* is also expected to identify new instances of this phenomenon around stars at distances of several thousand light-years.

In general, the present instrument complement is well suited for investigating solar system objects at low to moderate spectral resolutions with high sensitivity. It thus holds great promise for measuring their energy budgets, morphologies, and compositions, particularly for the solid-phase species (minerals and ices). The instrument complement also provides a unique capability for studying diffuse solar system emissions, such as the asteroidal dust bands discovered by the *IRAS*.

A weakness for planetary science lies in the fact that the highest spectral resolving power now planned for *SIRTF* will not be sufficient to resolve the vibrational bands of atmospheric molecules into their individual rotational lines. For stratospheric species (narrow lines), determining vertical distributions from thermal emission spectra will not be possible. In the short-wave infrared, identifying many of the interesting trace molecules will not be possible, because of line blending and overlap with the strong bands of other species. The determination of isotopic ratios will also be hampered. An improvement in *SIRTF's* usefulness for planetary astronomy would result from a significant increase in its spectral resolving power in the vibrational infrared.

Explorers

The Explorers are a line of free-flying spacecraft, managed within NASA's Astrophysics Division, that are designed to provide substantial in-orbit capability in relatively specialized areas of research. A recent Announcement of Opportunity for these missions excluded solar system objectives from consideration as the prime objective, although such systems as *IUE* and *IRAS* have been very productive for planetary science in the past. The Planetary Astronomy Committee deplores this exclusion, especially in view of the successes in the field with previous Explorers. The Committee recommends that some form of cooperative management be established between the various divisions of the Office of Space Science and Applications interested in the use of Explorers.

Of particular relevance for planetary studies is *Lyman,* an Explorer-class spectrographic facility that will cover the far ultraviolet region of the spectrum. *Lyman* is based on the recognized need for sensitive astronomical capability below 120 nanometers for a broad group of scientific areas, including planetary science. For example, the only strong emission from the O^{+} ion, present in carbon dioxide atmospheres and the Io torus, is at 83 nanometers. The strongest emissions of the Io torus and also from the outer planet aurorae appear in this spectral region, which is also important for studying the electroglow, noble gas abundances in planetary atmospheres, and the nitrogen emissions on Titan. *Lyman* could be a very powerful tool for planetary science, and although planetary scientists have been involved in the conceptual development of this proposed Explorer, we note that neither NASA's Solar System Exploration Division nor its advisory committees has had any formal participation in this project.

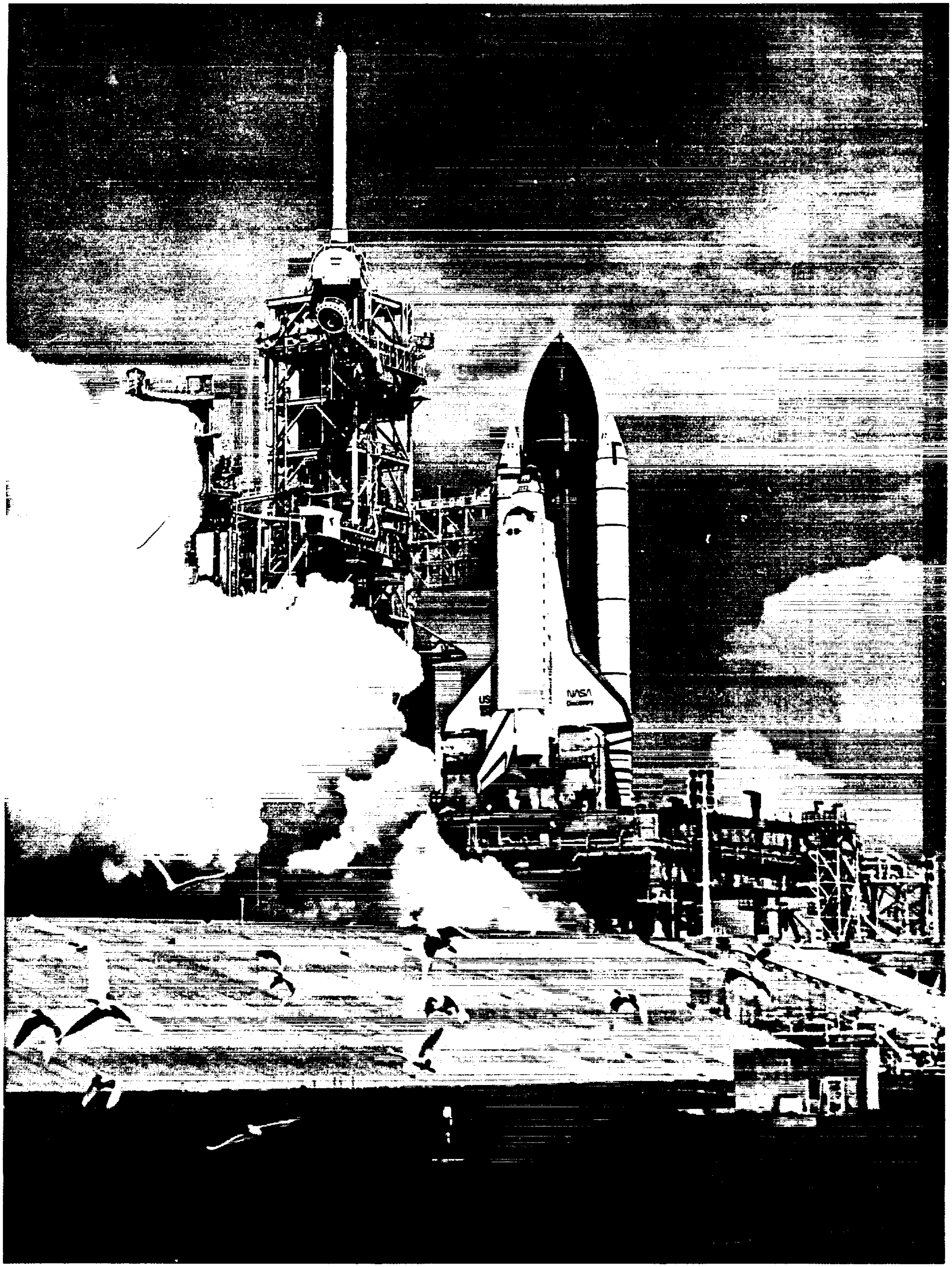
Small Shuttle Payloads: Astro, Spartan, and Hitchhiker

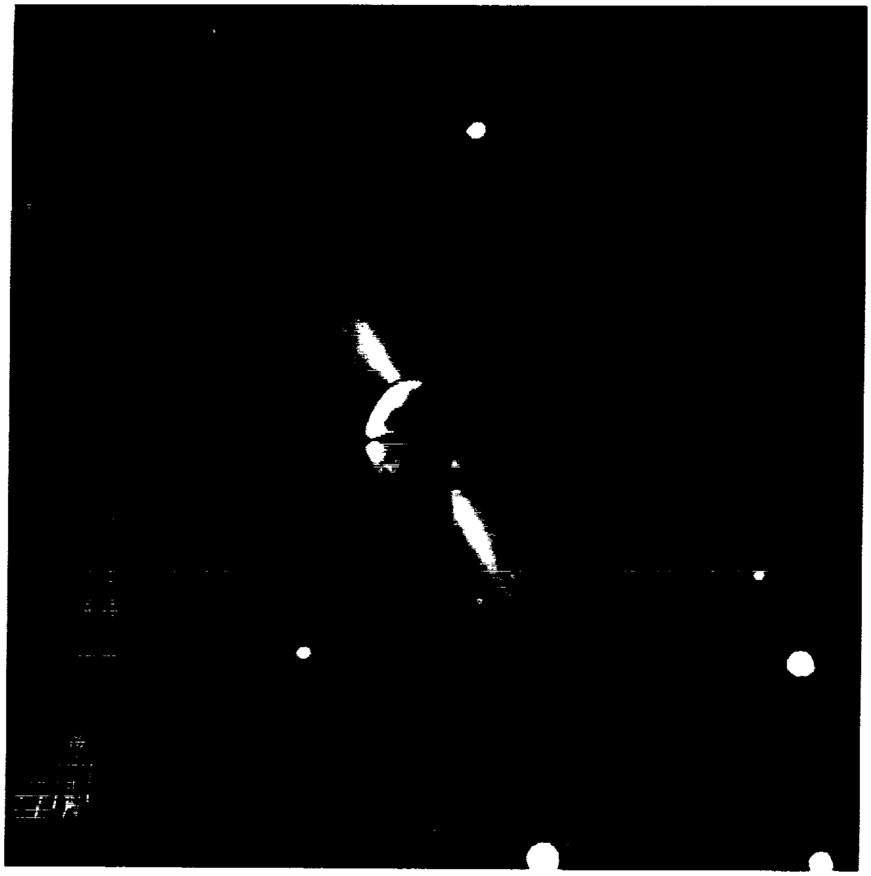
The Space Shuttle offers the capability for orbiting small research payloads for short intervals at specific times (for example, at the time of a newly discovered comet, or during a planetary mission encounter). In this section we note a number of payload types that have definite potential for creative contributions to planetary astronomy. All these payloads are managed by the Astrophysics Division; all need close attention by the Solar System Exploration Division to ensure that their potential for planetary astronomy is maximized.

The Astro (Astronomy Laboratory) payload is a cluster of three co-pointed telescopes for ultraviolet spectroscopy, imaging, and polarimetry. Astro is a Spacelab mission, originally planned for a March 1986 launch to study Comet Halley, and now rescheduled for flight in early 1989. A number of solar system observations are planned, and these could include the Io torus, outer planets, asteroids, and comets. Subsequent flights of the Astronomy Laboratory are expected to have substantial percentages of time (50 percent) for Guest Investigator Programs in which planetary scientists could participate.

Spartan and Hitchhiker are also Shuttle-attached payloads that are fully managed by the Astrophysics Division. Spartan is a carrier spacecraft that can provide a free-flying platform detached from the Space Shuttle for periods of a few days; Hitchhiker is basically a container for small scientific experiments that remains within the Shuttle bay during orbital flight. These systems were intended to

The Space Shuttle provides the capability for orbiting small research payloads. Pictured here is Discovery, *on its September 29, 1988 launch.*





One of the stars that IRAS *found to have an infrared excess (caused by a ring or disk of particles) is the southern hemisphere star Beta Pictoris.*

replace or enhance suborbital rocket capability and to provide experimenters with low-cost, rapid-turnaround access to space.

A Spartan payload designed for ultraviolet observations of Comet Halley was lost in the *Challenger* accident. Other Spartans, optimized for studying emissions from the Io torus in the extreme ultraviolet and for monitoring absolute solar fluxes in the ultraviolet, are currently under development. Two Hitchhiker payloads are presently being developed in conjunction with the United States Air Force. The first, which is capable of extreme ultraviolet spectroscopy, will soon be available and could be applied to the Io torus problem. The second is a 1 to 5 micrometer spectrometer that could be applied to a variety of solar system objects.

New Initiatives in Earth-Orbital Planetary Astronomy

Special Requirements of Planetary Observing

General-purpose astrophysical observatories cannot be expected to satisfy all the requirements of planetary astronomy. The astrophysical targets of greatest interest are usually very faint, intrinsically hot, and often very energetic. Consequently, astrophysical observatories are usually optimized for the ultimate in broadband photometric sensitivity. Spectroscopic capability emphasizes the measurement of spectral gradients and discontinuities, or strong broadened atomic lines for which modest spectral resolution is adequate. Where high-resolution spectroscopy is employed, as in the case of the high-resolution spectrometer on the *Hubble Space Telescope,* the instruments are optimized for point (stellar) sources fixed in the sky.

Although some solar system measurements can be adequately accommodated by such designs, many others have requirements that are not consistent with those for which the designs are intended. Chief among these is the need to observe very bright objects, particularly when they happen to be close to the Sun.

Other special requirements for planetary astronomy include:

- Critical timing for observation of occultations and planetary phenomena, or for coordination with measurements from planetary probes
- High-precision pointing and non-sidereal tracking
- Special software to allow targeting of moving objects and to provide accurate post-observation pointing knowledge
- Sensitivity below the Lyman limit
- Very high spectral resolution, particularly in the near infrared
- Need to observe variable phenomena simultaneously in widely separated spectral regions
- Need to sample phenomena frequently over very long periods of time.

Each of the above requirements has, at one time or another, created problems in the development of astrophysical projects. These problems have usually been resolved on an ad hoc basic with (at most) modest satisfaction to the participants. The Planetary Astronomy Committee recommends that the Solar System Exploration Division undertake the primary responsibility for achieving the full planetary potential of astrophysical observatories through suitable cross-program liaisons.

The Search for, and Characterization of, Other Planetary Systems

Perhaps the most significant new initiative for planetary astronomy in the 1990s will be to undertake a comprehensive search for (and then characterize the properties of) planetary systems beyond our own. The results of several studies over the past several years indicate that two promising and complementary Earth-orbital observational approaches to this problem exist: astrometry and direct imaging. A third approach, involving high-precision Doppler spectroscopy, can be, and is, carried out from the ground.

Studies of the problems of measuring the reflex motion of stars induced by orbiting planets have led to the concept of the *Astrometric Telescope Facility* (ATF), which can measure relative astrometric positions to a precision of 10 microarcsec. The primary goal of the ATF is the search for, and the study of, other planetary systems. This goal is motivated by a desire to test current ideas about the origin of our

The Circumstellar Imaging Telescope

The *Circumstellar Imaging Telescope* (CIT) is a proposed 1.5-meter diameter, Earth-orbital, low-scattered-light coronagraphic telescope. The primary objectives of the CIT will be to detect other planets around nearby stars and to image faint material near bright astronomical objects. To accomplish these objectives, the direct light from the planet must be examined without contamination from the light of the parent star, and the CIT's design meets this requirement. The telescope incorporates a special optical device, called a coronagraph, to block the direct light from bright stars, combined with a super-smooth mirror to reduce the glare that these stars generate.

Figure 6 depicts the components of the CIT. Three major elements comprise the system: the telescope, with primary and secondary mirrors; the coronagraph, consisting of a field lens, an occulting mask, a Lyot stop, and a relay lens and filter; and a camera that uses a charge-coupled device detector to capture images.

The diffraction control technology employs a principle that was first used in the 1930s to look at the corona of the Sun. The instrument, a Lyot coronagraph, works by blocking out the center light from a bright object in the field of view with an occulting spot in the focal plane. Downstream from this point, the pupil of the telescope is imaged and masked off to remove the contribution of light that is diffracted from the edges and secondary support structures of the primary and secondary mirrors. This allows the reimaging of the focal plane onto a detector with the diffracted component of light reduced by a factor of 100 to 1,000 from that of a conventional system.

The other key technology that allows the use of a low-scattered-light telescope is the fabrication of a super-smooth mirror. Mirror fabrication technology has not been driven by astronomical mirrors, but by other optical uses, such as the fabrication of micro-electronics. For example, microlithography mirrors (0.5-meter diameter spherical mirrors) have been characterized as being 5 times smoother than the *Hubble Space Telescope* mirror at mid-spatial frequencies. The metrology used to measure the figure of the mirrors can go beyond this specification, and no inherent reason prevents the fabrication of much smoother mirrors. A primary mirror 2 to 3 times better than the currently produced mirrors is needed for the direct detection and characterization of extrasolar planets. This level of mirror smoothness is currently within the capabilities of existing fabrication techniques.

The CIT is a concept that is mature enough to be implemented with current technologies. Both our understanding of diffraction control and recent advances in the fabrication of super-smooth mirrors could provide the necessary components for a 1.5-meter CIT by the mid-1990s. Such a system could be flown either as an attached payload on Space Station *Freedom* or as an independent free-flyer to address a broad range of extrasolar planetary and astrophysical scientific objectives. Furthermore, this initial system would provide a testbed for studying engineering and technical questions for larger future systems. The CIT would not only address the technologies necessary for complete remote characterization of discovered planets, but would also provide important data on circumstellar disks, zodiacal components, and protoplanetary material around nearby stars.

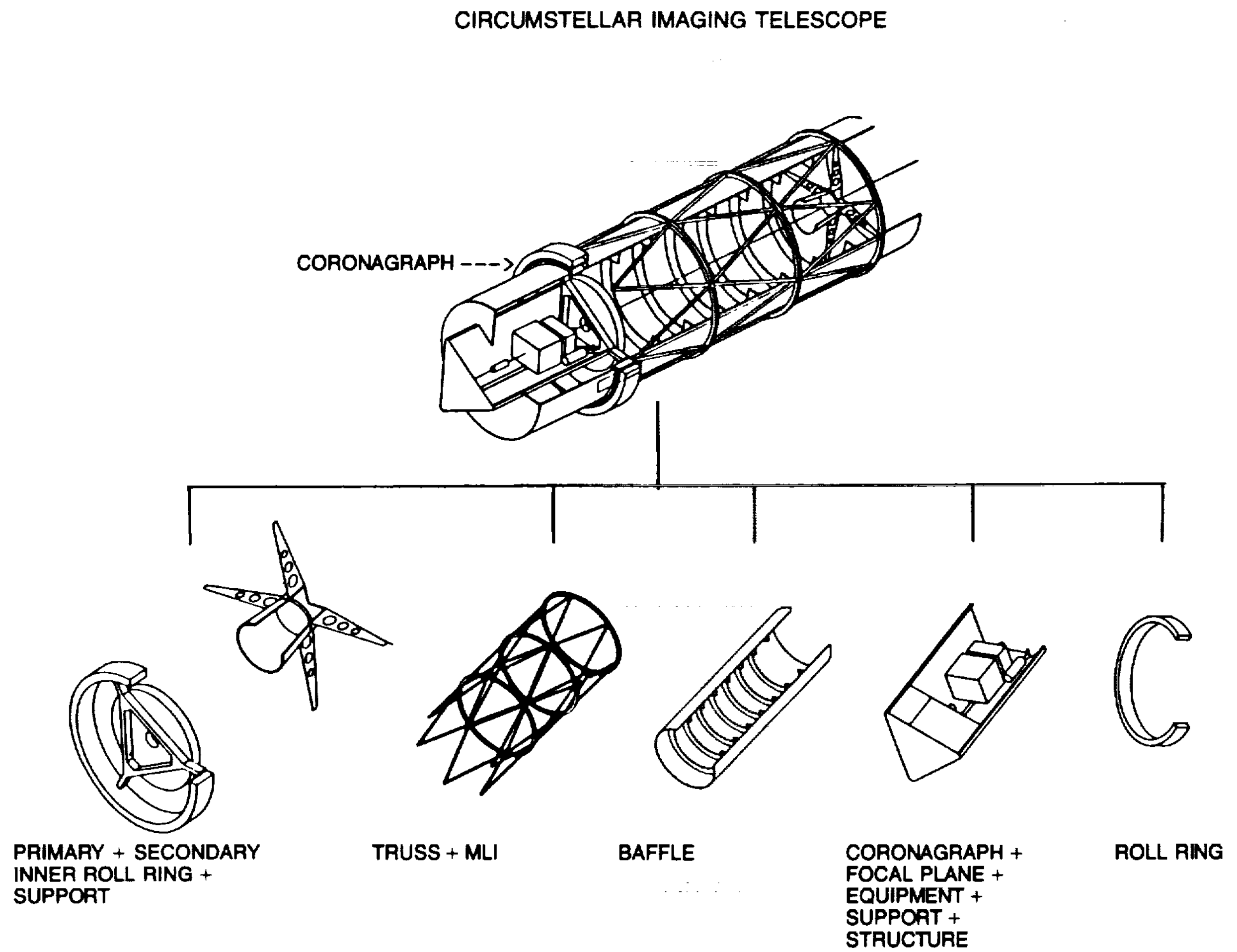

CIRCUMSTELLAR IMAGING TELESCOPE
CORONAGRAPH --->
PRIMARY + SECONDARY INNER ROLL RING + SUPPORT
TRUSS + MLI
BAFFLE
CORONAGRAPH + FOCAL PLANE + EQUIPMENT + SUPPORT + STRUCTURE
ROLL RING

Figure 6

solar system and further develop these ideas into a firm theory of star and planetary system formation and evolution. The ATF has already been identified as a candidate for early operation on Space Station *Freedom*, and we support the continued development of this concept.

The orderly nature of our solar system implies that it originated from a single precursor object. Present evidence suggests it was formed from a rotating cloud which, when acted on by viscous effects and self-gravitation, resulted in the overall configuration of the solar system. If this view is correct, then planetary systems are formed as a natural consequence of star formation, at least for single stars, and we may believe that our solar system is not unique. If, on the other hand, a statistically significant survey of stars shows our system to be unique, existing theories would have to be reexamined. Therefore, the basic astrometric goal is to examine nearby stars for evidence of planetary systems, and an important objective is to ensure that a negative result would be scientifically significant. To achieve these goals, the investigation should have the capability to detect planets as small as 10 to 20 Earth masses at distances on the order of 2 to 10 astronomical units from the central star and should investigate on the order of 100 candidate stars within 25 light-years from the Sun.

The ATF approach is to make astrometric measurements with respect to a frame of distant stars, to an accuracy that would show the reflex motion of a star. The survey is planned to last 10 to 20 years, but results will be provided continuously during the survey. Outer planet analogs may be discovered, revolving around M-class dwarfs with orbital periods of a few years. Although the ATF is being designed specifically for planetary detection, these capabilities will provide the opportunity for other important astrophysical investigations.

In a less advanced state of technical maturity and development is the concept of a low-scattered-light coronagraphic telescope for the direct detection of circumstellar material, and possibly even of planets around nearby stars. This concept, the *Circumstellar Imaging Telescope,* depends on a newly developed capability to make mirror surfaces to a precision not heretofore used in astronomical research. Over scales of tens of centimeters, the accuracy of the mirror surface must be held at levels that are many times more stringent than was the case for the *Hubble Space Telescope* mirror. Such accuracy is within the state of the art for small mirrors, and no reasons of principle seem to prevent the application of this technology to much larger mirrors.

The search for other planetary systems is a formidable technical task, and we are not certain that an unambiguous result will be forthcoming from the early results. The Solar System Exploration Division must develop and nurture this new field if it is to attain its goals. The time for a beginning is now. The problem should be approached in a phased way, through simultaneous development of two or three of the key methods that have been identified.

The Solar System Exploration Division should support the continued development of the above two concepts—the *Astrometric Telescope Facility* and the *Circumstellar Imaging Telescope*—in order to capture the earliest opportunity for their deployment. Development is required in order to reach a technical level adequate to identify interfaces and operational requirements on Space Station *Freedom*. The possibility of combining these two capabilities in a single instrument should also be vigorously investigated, perhaps through the pursuit of low-scattered-light optics for the ATF, with a dual focal plane that is capable of supporting both astrometric and imaging systems. Such a combined instrument would provide an extremely powerful facility for both the detection and characterization of planets and for detailed investigation of circumstellar materials associated with the formation of planetary systems.

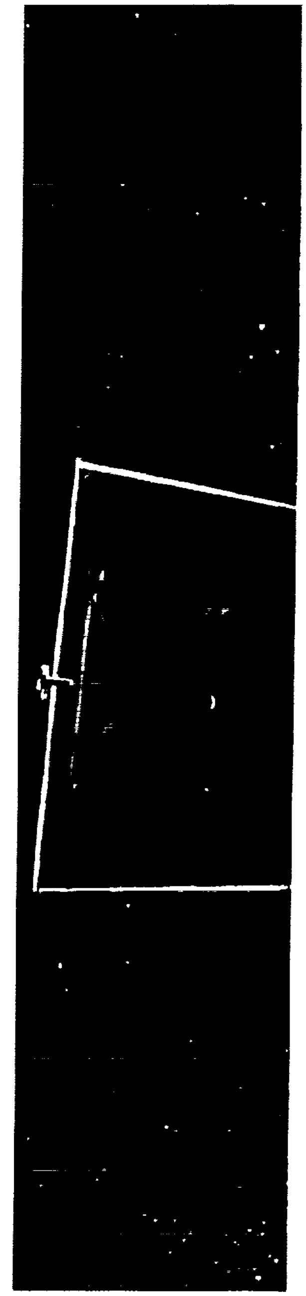
International Opportunities

As a part of this study, the Planetary Astronomy Committee has surveyed the potential for international cooperation in Earth-orbital planetary astronomy. The program of the European Space Agency includes a particular mission, the *Infrared Space Observatory,* which has strong solar system objectives and wide participation by European planetary scientists. This mission is planned for launch in 1993. Although direct cooperative involvement of the U.S. in that study is probably not possible now, future opportunities may exist for planetary scientists to participate as guest investigators in the actual flight mission. Clearly, developing an agreement with the European Space Agency regarding U.S. guest investigator arrangements on the *Infrared Space Observatory* would be in the best interest of the Solar System Exploration Division.

Two other international possibilities merit special consideration. The first is an initiative by planetary scientists in the Federal Republic of Germany to develop a free-flying telescope especially designed for solar system studies as part of their national space program. The idea of a free-flying orbital telescope that is essentially dedicated to planetary astronomy is not a new one; however, because of the substantial funding commitment such a telescope would require, it has never been proposed for the U.S. program. The realization of this German initiative would revolutionize Earth-orbital planetary astronomy, because it would provide a capability for extended, optimally sampled observing programs with instrumentation uncompromised by the requirements of our colleagues in the astrophysics discipline.

The German *Planetary Telescope (Planetenteleskop)* is conceived around a 1-meter aperture telescope with a high-resolution (0.1 arcsec) imaging capability and the underlying philosophy that the telescope should be capable of simultaneous measurements in widely separated spectral regions (ultraviolet through infrared). This telescope is now entering a preliminary study phase, and substantial opportunities exist for U.S. participation in terms of intrumental hardware, launch system, and scientific investigations. For example, this telescope could incorporate the kind of low-scattered-light coronagraphic camera system needed to directly image circumstellar environments. Since the concept is new, possibilities also exist for advanced instrumentation operating in the ultraviolet and the near infrared that simultaneously combine imaging and spectroscopic capability.

The second project is the result of a joint initiative by Italian and U.S. scientists to develop an Explorer-class telescope system for general-purpose astronomical use. Although not specifically conceived for solar system studies, the concept, called *Argus,* is partially intended for simultaneous multispectral monitoring of solar system phenomena. *Argus* includes a substantial capability for spectrographic observations throughout the ultraviolet. The concept also includes, as part of a powerful combination of imaging spectrographs, a special system to monitor simultaneously the ultraviolet spectrum of the Sun, a capability that is of great importance to future planetary research in the ultraviolet.



Summary Recommendations for Earth-Orbital Planetary Astronomy

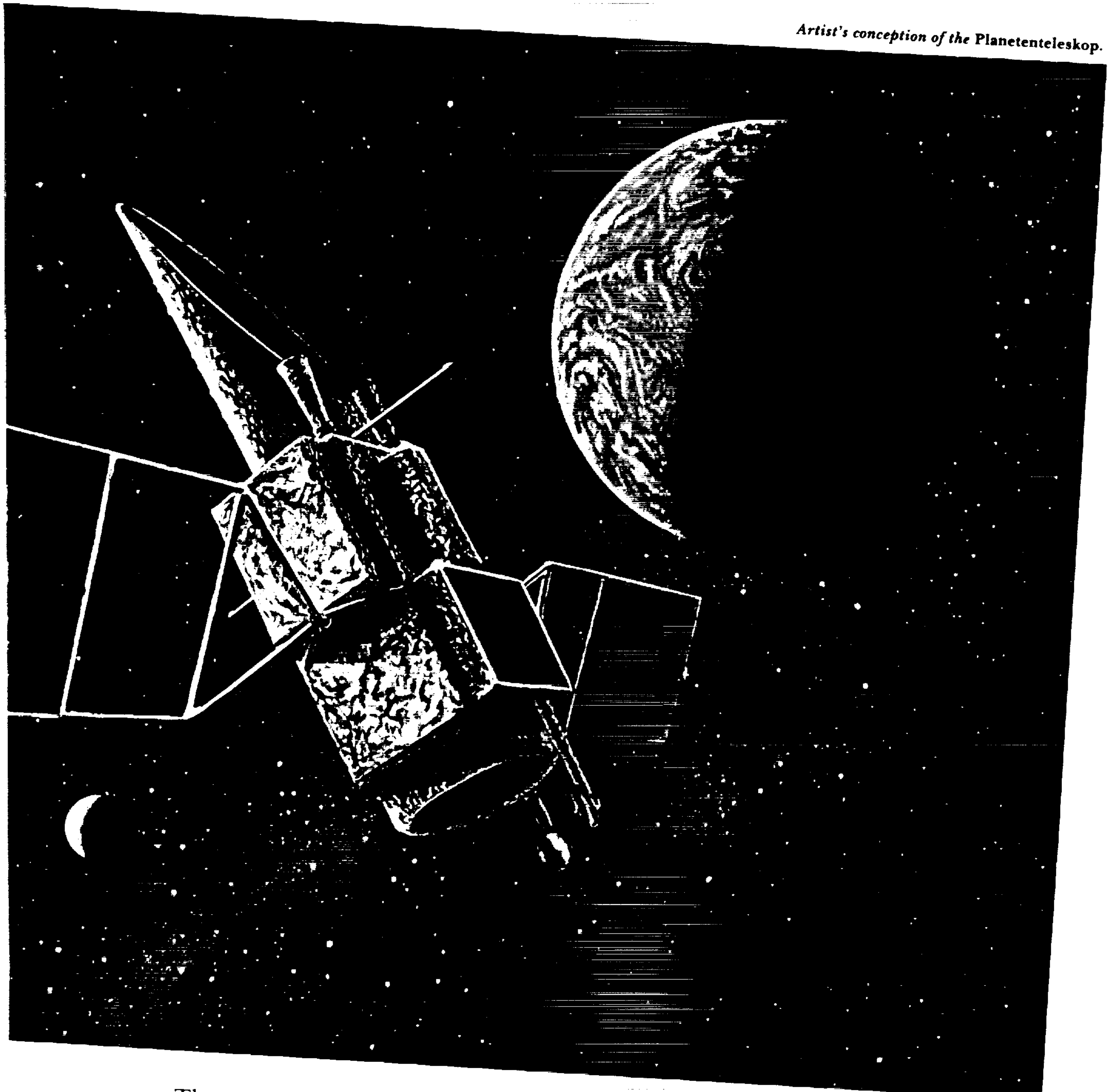
Unlike ground-based and airborne planetary astronomy, the prospects for Earth-orbital investigations lie mainly in the future, and so substantial opportunities exist to plan for their use. In fact, collaboration must begin immediately in order for the Solar System Exploration Division to participate in and use the many upcoming facilities in the Astrophysics Division. Efforts in Earth-orbital planetary astronomy that are associated with goals in our own solar system should be paced to the progress of the program of planetary flight missions. Efforts to achieve the broader goals associated with the study of other planetary systems should be promoted in parallel, but at the rate allowed by available resources. We have defined a short-term program and indicated what we see as fruitful areas for Earth-orbital planetary astronomy in the longer term.

Short-Term Plan

- Assure maximum potential in planned astrophysical observatories for planetary astronomy, with immediate emphasis on ensuring the ability of the *Hubble Space Telescope* to meet its design goals for pointing and tracking of planetary targets.
- Support *SIRTF,* and study the inclusion of a high-resolution planetary spectrographic instrument in the flight payload.
- Continue to support the development of the *Astrometric Telescope Facility* concept, and begin to fund feasibility research and concept development of a low-scattered-light, coronagraphic telescope for the direct detection of other solar systems.
- Collaborate with international partners wherever feasible.
- Use the Space Transportation System's attached payload capabilities.

Long-Term Plan

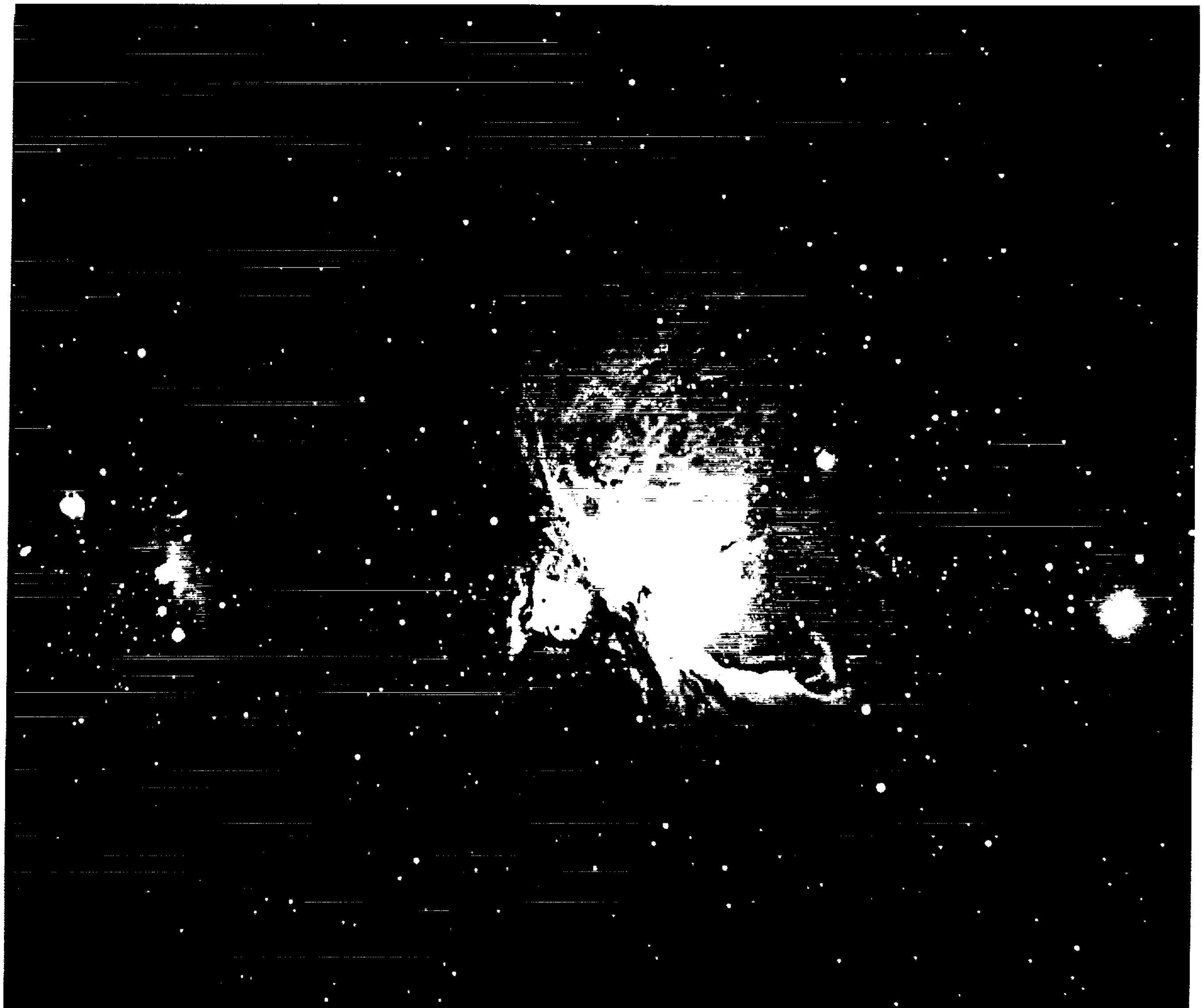
- The new objective to locate and characterize planetary systems elsewhere in the Galaxy should be pursued in the context of Space Station *Freedom* development, or possibly as part of an international collaboration in a free-flying Earth-orbital telescope system. Pursuit of this objective should include development of systems designed for both astrometry and direct imaging.



Artist's conception of the **Planetenteleskop.**

• The Solar System Exploration Division should develop a position on future free-flying Earth-orbital facilities dedicated to solar system objectives, with particular consideration given to systems in the Explorer class and to opportunities for international collaboration, such as the *Infrared Space Observatory*, the German *Planetary Telescope*, and concepts such as *Argus*.

The Great Nebula in Orion: an active region of star formation.



Conclusions and Recommendations

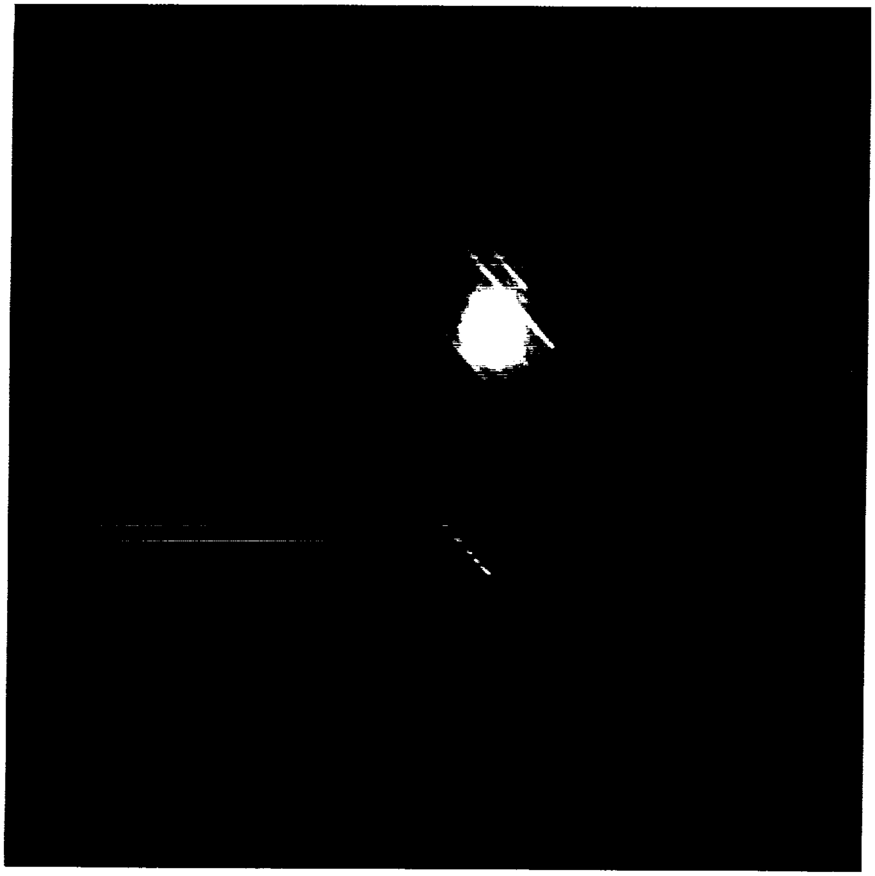
Planetary astronomy—the study of planetary bodies and phenomena by the remote-sensing techniques of ground-based, airborne, and Earth-orbital observations—led the way as we began our detailed exploration of the solar system. Planetary astronomers, working at mountaintop telescopes and with radar instruments, or from the Kuiper Airborne Observatory, or using the *International Ultraviolet Explorer* and the *Infrared Astronomical Satellite,* have discovered and broadly characterized many of the planets, satellites, rings, asteroids, and comets that make up our planetary system. Planetary astronomers have interpreted and synthesized the data they have obtained, developing theories and working in laboratories. These scientists have charted the orbits of the planetary bodies, and they have provided the initial characterization of the planets' environments, necessary to plan the first planetary probes by spacecraft. Even today, in the era of spacecraft exploration of the solar system, astronomical techniques still yield much of the information we have on the composition of the surfaces and atmospheres of most of the planets and satellites. Astronomical techniques probe, with high resolution, the dynamics of the rings of Uranus; they map the surfaces of Venus, Mercury, and the asteroids; and they provide us information about the populations of primitive asteroids and comets that remain from the era of solar-system formation. In addition, as we expand our perspective to embrace the search for other planetary systems and to probe the details of star and planet formation, we must rely exclusively upon advances in the astronomical discipline.

In the coming decades, planetary astronomy can anticipate many exciting new opportunities, which bring with them considerable challenges. The opportunities derive from powerful new technology and instrumentation, on the ground, in the air, and in Earth orbit. The challenge that planetary astronomy must meet is to develop a strategy, in an environment constrained by fiscal and other conditions, that maximizes the benefits accrued from taking advantage of these new opportunities. To reestablish itself as a vital, productive field of scientific endeavor, planetary astronomy must move forward and grow.

We have described the elements, objectives, and status of NASA's Planetary Astronomy Program, and we have discussed the critical ways in which planetary astronomy contributes to the goals of the overall program of solar system exploration. The availability of funding and facilities is disproportionately small, compared with the scope of potential study and discovery. While opportunities and technological sophistication are advancing, budgets, access to technology, and the infusion of new scientists are languishing. To define a future program that considers these facts and points the way to begin to reverse this trend, we have assessed the numerous possibilities before us, and we have attempted to define priorities for their application to planetary astronomy.

Several techniques are used for ground-based and airborne observations of our solar system. Each technique provides an especially valuable capability for a particular type of object or phenomenon. For example, photometric methods are being used to study Pluto and its satellite, Charon, during the epoch of mutual eclipses, transits, and occultations. Our knowledge of this very distant planet comes almost entirely from ground-based measurements. This is likely to remain the case for quite some time; no spacecraft missions to Pluto are planned in the future. Spectroscopy and spectrophotometry, also basic techniques of astronomy, are the sources of much current information on surface and atmospheric chemistry in the solar system. Although the next generation of planetary spacecraft is expected to include new instruments for remote spectral analyses of surfaces and atmospheres, astronomical studies from Earth will continue to provide unique information on compositions. Further, Earth-based observations permit this information to be studied in a temporal and spatial context that is rarely, if ever, available to a flyby or orbiter spacecraft. A third

Comet IRAS-Araki-Alcock as it appeared on the night of May 8, 1983.



example is to be found in the capability of radar to probe through the clouds of Venus and the obscuring dust of comets, and to study many planetary characteristics on spatial scales of only tens of centimeters, set by the radar wavelength itself—scales orders of magnitude smaller than those probed by most other techniques.

All the methods currently used—photometry, spectrophotometry, spectroscopy, imaging, polarimetry, occultations, radar, radio, and astrometry—combine to generate a rich source of data on our planetary system. Enhanced funding, broader support for research and data analysis, significant improvements in instrumentation, and increased availability and flexibility in the provision of telescopes to planetary astronomers can greatly enhance the productivity of this endeavor.

Rapid advances in detector technology offer enormous improvements in instrument sensitivity, spectral resolution, and wavelength coverage, but in the past decade, planetary astronomers have generally been unable to obtain funding to take advantage of these developments. Much observational work that is directly relevant to NASA programs cannot be accomplished because of a serious and long-term lack of the financial support required for the construction and implementation of front-line instrumentation for ground-based and airborne telescopes. In addition, a shortage of observing time has always existed on ground-based and airborne telescopes, and it is important that planetary astronomers have access to the new optical-infrared telescopes now under construction or planned.

Two decades of research and discoveries using small orbiting astrophysical observatories have illustrated the usefulness of Earth-orbital systems for planetary astronomy. Because certain classes of investigations require extended wavelength coverage, a global view, and freedom from the interference generated by Earth's turbulent atmosphere, these investigations must be carried out from Earth's orbit. In the future, exciting prospects for this relatively new technique will be well within reach. Many of these opportunities exist outside the Planetary Astronomy Program and the Solar System Exploration Division of NASA. If planetary astronomy is to realize the potential offered by new observatories in low-Earth orbit, considerable coordination, communication, and cooperation with the NASA Astrophysics Division and other relevant organizational entities are required. In addition, significant opportunities exist for participation in the international arena. Earth-orbital planetary astronomy represents a significant endeavor that is complementary to the program of flight missions and ground-based planetary astronomy, but a major augmentation of resources will be required to support it.

Advances in the sensitivity and spatial resolution of ground-based telescopes, the program of Great Observatories in Earth orbit, Space Station *Freedom,* and significant improvements in instrumentation combine to present a substantial potential for the attainment of additional objectives for planetary astronomy—the search for and characterization of other planetary systems, and a related effort to study the formation of planets in the circumstellar environments of protostars. Some of these studies can be undertaken from the ground, but others require instruments in Earth orbit. Future long-term orbiting observatories and telescopes, either free-flyers or payloads attached to *Freedom,* offer valuable facilities to determine the uniqueness or non-uniqueness of our solar system. The discovery and characterization of a system of planets circling another star would be a scientific breakthrough of fundamental importance. Only a political, institutional, administrative environment that can sustain the long-term commitment required for such an undertaking could make this discovery, and the subsequent characterization of such external systems, possible.

The balance of this chapter contains the Planetary Astronomy Committee's recommendations to the Solar System Exploration Division and the Solar System Exploration Management Council. These recommendations have been formulated to create a balanced program of ground-based, airborne, and Earth-orbital planetary astronomy that takes full advantage of state-of-the-art technology and of activities taking place both within and external to the Solar System Exploration Division. Some of these recommendations concern management and programmatic issues that must be addressed through effective interfaces between the Solar System Exploration Division and the National Science Foundation, and also other elements of NASA, particularly the Astrophysics Division.

The Planetary Astronomy Committee was formed to assess the current status of planetary astronomy, and to recommend a plan for a vigorous, rewarding, growing program of research. As repeatedly emphasized throughout this report, the Committee finds that the Planetary Astronomy Progam has been both productive and cost-effective in the past, and has great potential for continuing to do so in the future. Particularly in a period when the intervals between major deep-space missions are long, and flight opportunities for training students and responding quickly to new discoveries are limited, the Planetary Astronomy Program could and should assume an even greater significance. The Planetary Astronomy Committee urges NASA to reaffirm the importance of this activity and to recognize the essential role played by astronomical research in complementary support of flight missions and of other research and analysis programs. Planetary astronomy, along with cosmochemistry, planetary geology and geophysics, and space physics, provides a balanced, broad approach to solar system science.

Although the recommendations articulated here focus on future initiatives, the Planetary Astronomy Committee emphatically recommends that solving existing problems, as described in previous chapters, be of the highest order of priority. Only when the current Planetary Astronomy Program is relieved of some of the pressures of reduced funding and inadequate access to available instrumentation can the program begin to move forward with the recommendations for the future.

Recommendations for Ground-Based and Airborne Planetary Astronomy

To take advantage of potential new instrumentation and opportunities to expand the capability and utility of ground-based and airborne facilities, the Planetary Astronomy Committee makes the following recommendations.

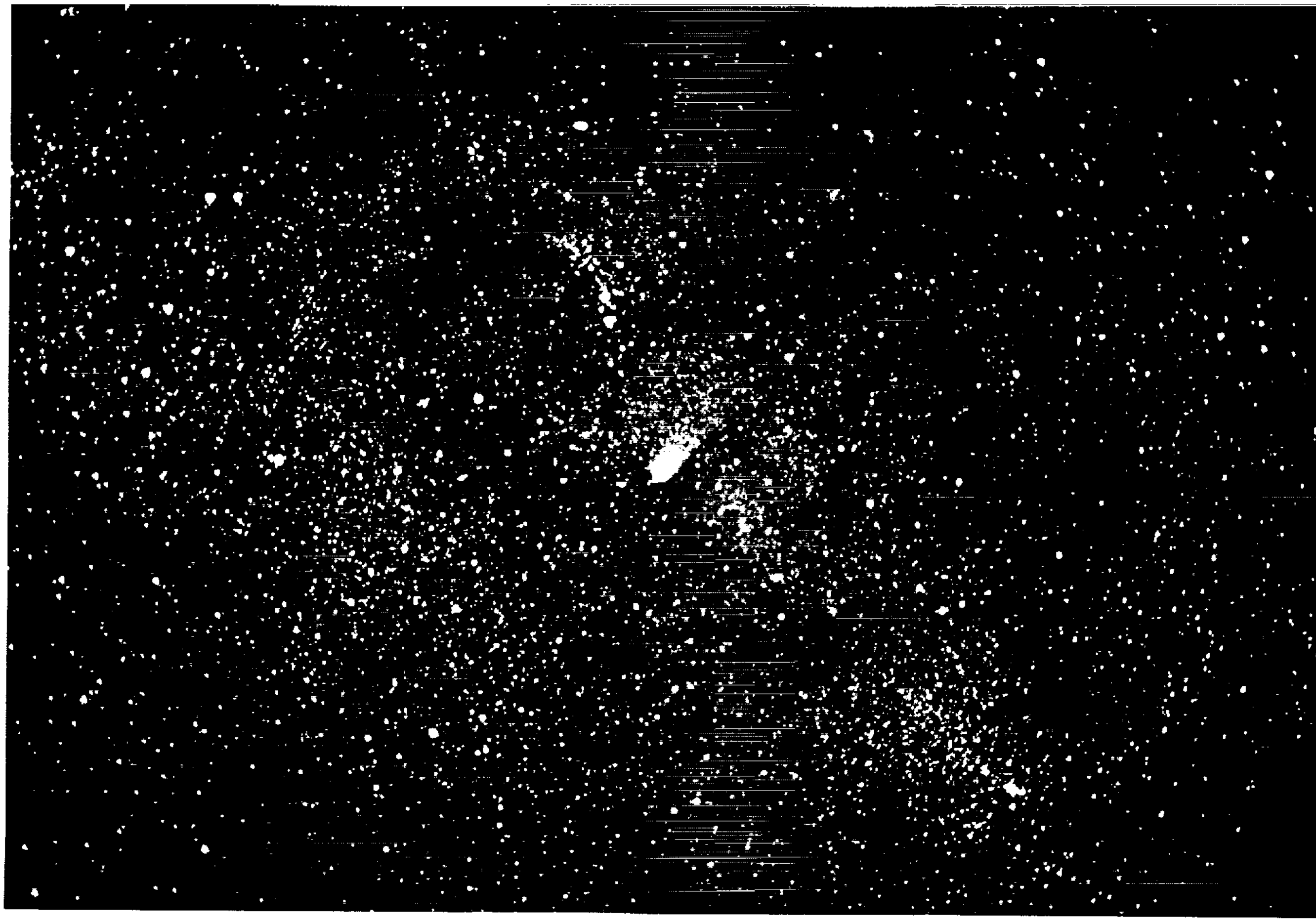
Existing Research Groups. Reinvigorate the strength of existing research groups so that they can afford cost-effective research assistants and technicians, modern computers, and other infrastructure necessary to efficiently and creatively pursue planetary astronomical research.

New Opportunities. Reopen opportunities for new researchers, especially younger ones, to enter the Planetary Astronomy Program by resuming or initiating support for undergraduate and graduate student research assistants and by augmenting the supply of funds for which new Principal Investigators might successfully propose.

Enhanced Funding. Reestablish scientific breadth in the Planetary Astronomy Program by enhancing funding, especially for such topics as supporting laboratory studies, theory, interpretation, and synthesis.

Access to New Telescopes. NASA must plan for the 1990s, when 8-meter and larger telescopes will be built. The planetary astronomy community needs to be involved in the development and use of this new generation of telescopes and, therefore, the Solar System Exploration Division may need to provide at least partial support for one or more of these telescopes to assure that the planetary astronomy research required to support the NASA mission can be successfully carried out. NASA should initiate discussions with the National Optical Astronomy Observatories or other interested parties

This photograph of Comet Halley crossing the Milky Way was taken from the Kuiper Airborne Observatory in March 1986.



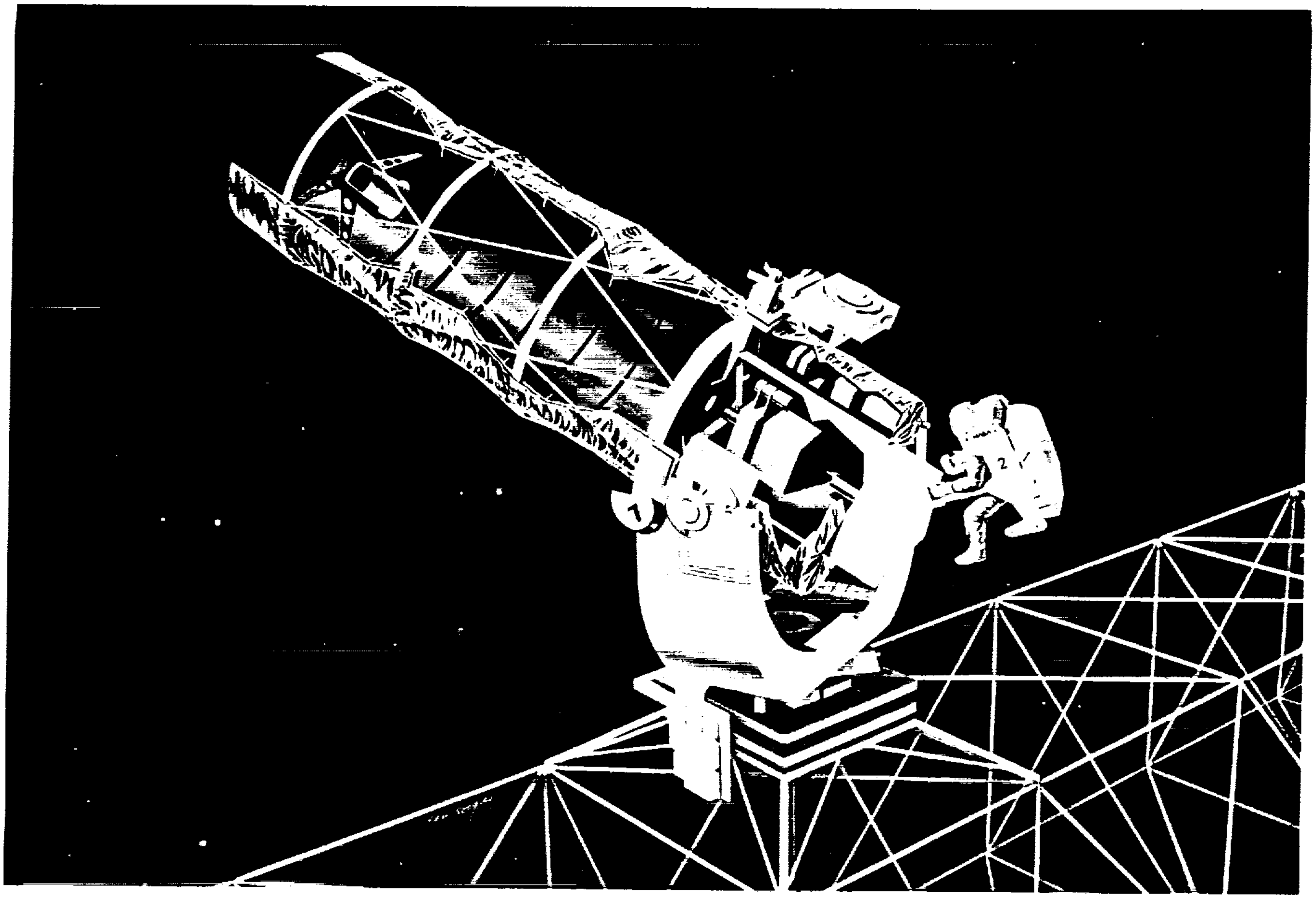
with the intention of developing a partnership to ensure that new facilities will be used to support planetary astronomy in the mid-1990s and beyond.

Applications of New Technology. Technological advances, such as improved sensitivity and new detector arrays, must be implemented in astronomical instruments for use by planetary scientists on large ground-based or airborne telescopes. A special development program for astronomical instrumentation should be started.

Kuiper Airborne Observatory. Increased support for additional, longer flights of the Kuiper Airborne Observatory is needed. A strong program for the development of new instrumentation for the Observatory should formulated and implemented.

SOFIA. SOFIA will provide important and unique capabilities for planetary astronomy, and the near-term development of this Stratospheric Observatory for Infrared Astronomy should be supported by the Solar System Exploration Division. In addition, an effort should be made to design the telescope and aircraft interface of SOFIA in such a way as to produce seeing that is generally 1 arcsec or better. To the degree that these requirements are set by planetary needs, the Planetary Astronomy Program may need to contribute funds for this development.

The **Circumstellar Imaging Telescope**, *a 1.5-meter low-scattered-light coronagraphic telescope, is shown here attached to Space Station* **Freedom**.



The Arecibo Radar. The proposed upgrades to the Arecibo radar, in particular the Gregorian feed, will enhance its power for planetary studies by more than an order of magnitude, and will allow the radar to probe hundreds of asteroids, comets, and planetary satellites that now lie beyond its range. These upgrades to Arecibo should be implemented as soon as possible.

Ground-Based Detection of Other Planetary Systems. Although space-based systems will ultimately be required to characterize other planetary systems, the initial discoveries are likely to come from ground-based facilities. One unique ground-based technique is high-resolution doppler spectroscopy, which is sensitive to giant planets in compact systems orbiting the common K and M dwarf stars. NASA should provide leadership and financial support to carry out doppler spectroscopy surveys in conjunction with other methods of searching for other planetary systems. At the same time, NASA should vigorously advocate, with the National Science Foundation, the development of a dedicated ground-based astrometric telescope, located at a favorable site, of 1- to 2-meter aperture to extend the search for other planetary systems beyond the limited capability of current astrometric and doppler-spectroscopy programs; such an instrument should be capable of detecting any "Jupiters" or "Saturns" that may exist around any of a hundred nearby stars.

Extrasolar Planetary System Detection: Strengths and Weaknesses of a Few Proposed Techniques

Technique	Strengths	Weaknesses
Ground-Based Doppler Spectroscopy	• Very low cost; can use existing facilities • Already begun, with 5-year time base • Can be used to great distances • Most sensitive to "compact" systems	• Probably limited to largest planets due to variations in stellar atmospheres • Good for detection of large planets but limited capability for further system characterization • Cannot detect small planets
Ground-Based Astrometry	• Fairly low cost • Most sensitive to "extended" systems • Excellent testbed for space-based ATF	• Requires construction of dedicated telescope at excellent site • Limited to Jupiter/Saturn size planets around nearby stars
Space-Based Astrometry (ATF)	• Most powerful approach for nearby stars (can detect Uranus/Neptune-size planets) • Excellent for continuing dynamical characterization of systems • Not limited by systematic errors (so far as we know) • Positive or null result will have profound impact on theories	• Very expensive • Requires long-term space platform, such as Space Station *Freedom* • Not likely to begin survey for a decade • Some risk in large jump from current systems to long-term platform
Circumstellar Imaging Telescope (CIT)	• Powerful for study of circumstellar environments • Most sensitive to large planets in "extended" systems • Useful for characterizing planets after discovery	• Very expensive • Requires long-term space platform • Not likely to begin work for a decade • Not optimum for initial dectection of planets (limited to large planets)

Recommendations for Earth-Orbital Planetary Astronomy

Study of the bodies of our solar system from Earth orbit, using the Great Observatories developed by the Astrophysics Division and other planned facilities, is a potentially major area of growth for planetary astronomy in the 1990s. Planned or proposed planetary-specific facilities in Earth orbit could change the scope of planetary astronomy. In addition, an enhanced objective for planetary astronomy—to search for and characterize other planetary systems—can best be met by long-term observations in Earth orbit. To make a program in Earth-orbital planetary astronomy a component of NASA's Solar System Exploration Program, the Planetary Astronomy Committee makes the following recommendations.

The Hubble Space Telescope. The *Hubble Space Telescope* should be optimized for planetary observations. To fully achieve its maximum capability for making solar system observations, adequate resources must be available for data reduction and analysis. Issues of the ability of this instrument to point and track planetary sources are of special concern; without this pointing and tracking capability, the *Hubble Space Telescope* cannot realize its promise for solar system astronomy. We recommend that the *Hubble Space Telescope* meet its originally stated requirements to track any target or feature of planetary interest. For the future, the Solar System Exploration Division must involve itself in the definition of second-generation instrumentation for the *Hubble Space Telescope.*

The Space Infrared Telescope Facility. The Solar System Exploration Division should be supportive of the development of the *Space Infrared Telescope Facility* and should investigate the possibility of including a high-resolution planetary spectrographic instrument in the flight payload.

The Explorer Program. The most recent Explorer Announcement of Opportunity from NASA excluded solar system science from consideration as the prime objective. The issue of planetary astronomy participation in the Explorer program should be reexamined, and planetary astronomy's use of this program, particularly for the upcoming *Lyman* facility, should be reestablished.

Space Shuttle Payloads. Close attention should be paid to maximizing the potential of Space Shuttle payloads, such as Astro, Spartan, and Hitchhiker, for planetary astronomy. These capabilities provide rapid access to space for ongoing temporal coverage of solar system phenomena, and they provide a base for the technical development of space instrumentation.

Astrometric Telescope Facility. Strong support should be provided for the continued development of the *Astrometric Telescope Facility* concept to capture the earliest opportunity for its potential deployment on Space Station *Freedom.* This facility, with its capability to detect planets as small as 10 to 20 Earth masses for 100 or more candidate stars, is the only proposed planet-detection system for which a negative result, as well as a positive one, will be highly significant.

With the current state of technology, it is also the only such instrument capable of characterizing a multi-planet system once it has been discovered.

Circumstellar Imaging Telescope. Significant funding is required for feasibility research on this low-scattered-light, coronagraphic telescope for the direct detection of other planetary systems and the characterization of other circumstellar phenomena. The ability of this imaging telescope to study precursor disks complements the ability of the *Astrometric Telescope Facility* to study mature planetary systems. NASA should study the possibility of combining the *Astrometric Telescope Facility* and the *Circumstellar Imaging Telescope* into a single cost-effective instrument.

International Collaboration. The Solar System Exploration Division should investigate and pursue participation with the planetary astronomy programs of other nations, such as the European Space Agency's *Infrared Space Observatory*, the German *Planetary Telescope*, and the Italian *Argus* program.

Management Issues

The effective implementation of these recommendations mandates considerable effort by NASA management to coordinate activities both within NASA and external to NASA. Fundamental management issues must be addressed to reverse the declining strength of the Planetary Astronomy Program and to take full advantage of the scientific challenge and the potential of late-20th Century technology. These issues are articulated below.

Role of Planetary Astronomy. The NASA Solar System Exploration Division should reaffirm its commitment to Earth-based astronomy as an essential component of a balanced program of solar system exploration. Planetary astronomy provides direct support for flight missions, and it generates vital complementary data that cannot be obtained by planetary probes. The United States' position of strength today in the discipline of planetary astronomy is almost totally due to the support that NASA has provided in the past, and NASA's continuing leadership and funding support are essential to the future health and productivity of this enterprise. The Committee encourages NASA to recognize a broad mandate for planetary astronomy, which includes the search for other planetary systems and an improved understanding of the process of planet formation in other systems, as well as our own.

Communications at NASA Headquarters. Planetary astronomy, which is supported by the Solar System Exploration Division, has important connections to the Astrophysics Division. In particular, many existing and planned major facilities with powerful capabilities for airborne and Earth-orbital planetary astronomy are going to be supported by the Astrophysics Division. Regular and effective communication between these two Divisions, combined with a willingness to cooperate on projects of mutual interest, is essential. The Committee urges that appropriate channels of communication be formalized and that these channels do not remain entirely dependent on the good will of the responsible individuals in each Division.

Planetary representation in the planning and management of Astrophysics facilities. The special needs of the planetary community must be recognized at all levels in the planning and execution of missions supported by the Astrophysics Division. They must be evaluated in a fashion that gives appropriate weight to the geological and geochemical goals that they address, which often are not considered by astrophysicists. Appropriate discipline scientists from the Solar System Exploration Division should be invited to serve as Deputy Program Scientists for missions, such as the *Hubble Space Telescope* and the *Space Infrared Telescope Facility*, that will be useful for planetary observations. Similarly, the Solar System Exploration Division should invite representation from other Office of Space Science and Applications divisions as Deputy Program Scientists in planetary flight missions that cut across division lines. The planetary community should also be represented in the planning and study groups working on future Earth-orbital and airborne astronomical facilities.

Communication and management issues between NASA and the National Science Foundation. The Committee recognizes the historically dominant role played by NASA in the support of planetary astronomy, but we are concerned by what appears to be continuing neglect by the National Science Foundation, in both its national facilities and its grants programs, of this branch of astronomy. For example, the role of planetary astronomy at the National Optical Astronomy Observatories has declined dramatically over the past 15 years, in spite of the growth of this discipline elsewhere. Fundamental issues exist concerning the access of planetary astronomers to the new telescopes now being planned in the 6- to 10-meter class. We encourage NASA and the National Science Foundation to continue regular, close communication in the area of planetary astronomy, and to continue to reexamine issues concerning the division of effort between the two agencies.

Access to telescopes. If planetary astronomers are to effectively pursue their research, they must have access to telescopes. We commend NASA for its foresight in constructing ground-based telescopes dedicated to planetary observations, and for its continuing support for the operation of such telescopes. These instruments are essential to the continued productivity of planetary astronomy. But we are concerned about limited access to the many other telescopes now operating or being constructed. A continuing need exists for appropriate representation of the planetary community in telescope scheduling, especially so that astronomers can be responsive to targets of opportunity, such as newly discovered comets and Earth-approaching asteroids. Although this is not primarily a NASA issue, we ask that the Solar System Exploration Division be sensitive to this problem and use its influence where appropriate in representing the special needs and concerns of planetary astronomers.

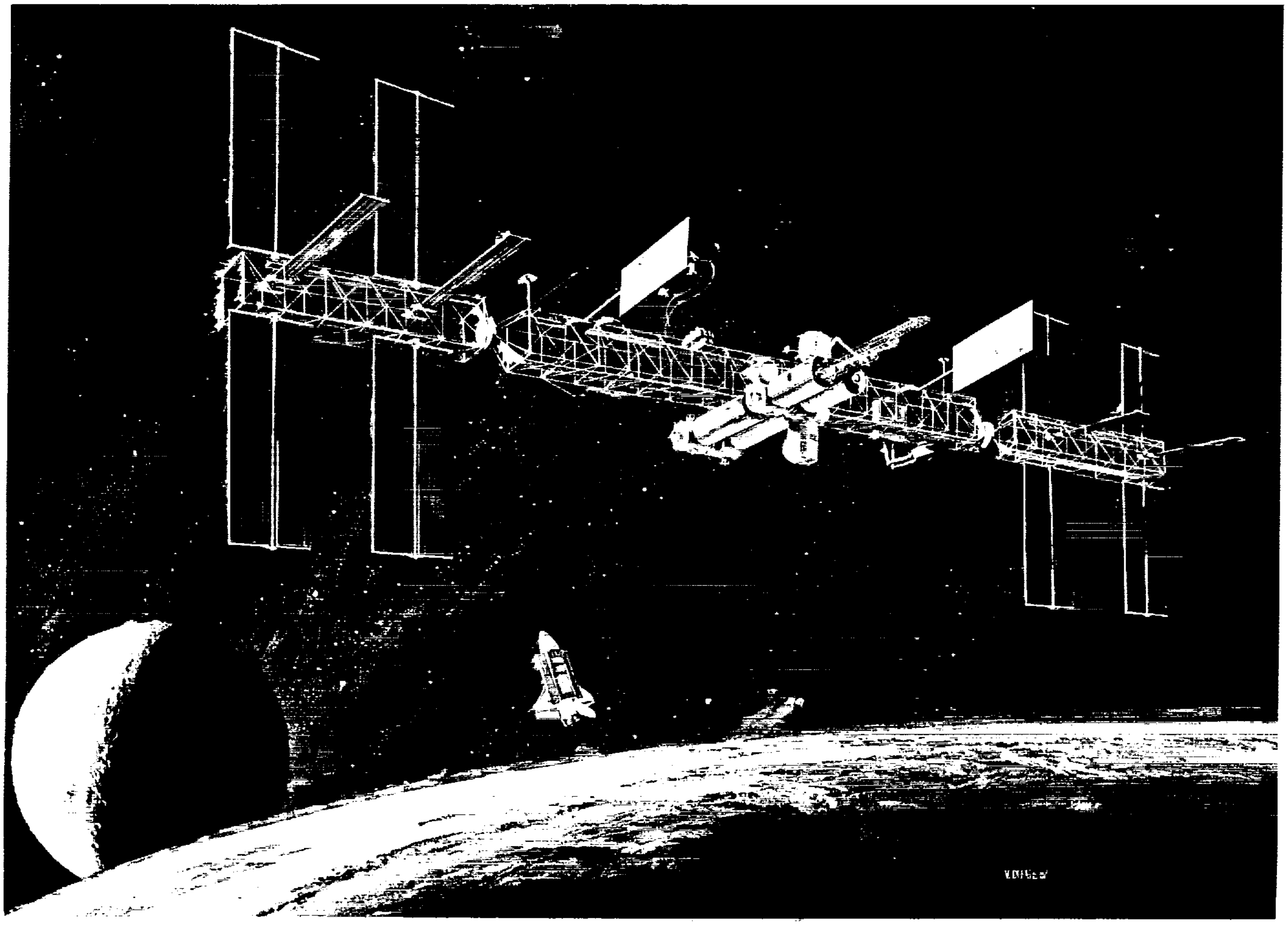
Requirements for instrument development for planetary observations. Both this Committee and the Planetary Astronomy Management Operations Working Group have concluded that a number of specialized planetary instruments are needed, such as Arecibo radar upgrades and facility instruments at the Infrared Telescope Facility. Although the Planetary Astronomy Program at NASA has expressed the desire to reinstate its support of some instrument development, this particular activity has received essentially no funding in recent years. The Committee is concerned that the development of instruments optimized for planetary work has not been vigorously pursued, and we recommend that attention be given to redefining the focus of responsibility for such support.

The role of planetary Earth-orbital work. The Planetary Astronomy Committee is concerned that the current division of effort between the Solar System Exploration and Astrophysics Divisions at NASA can lead to missed opportunities in the use of Earth-orbital astronomical facilities for planetary observations. So that the planetary science community can take full advantage of the opportunities provided by these facilities, and so that it can participate in their development, we recommend that the Solar System Exploration Division, in conjunction with the Astrophysics Division, promote and support workshops on Planetary Astronomy and the Great Observatories. Furthermore, within the Solar System Exploration Division, a permanent management working group should be formed. The charter of this group is to be fully informed of the potential planetary capabilities of projects sponsored by other NASA divisions, to undertake the responsibility of alerting the Solar System Exploration Division to opportunities for maximizing the potential of these projects for planetary astronomy, and to develop Earth-orbital opportunities within the Solar System Exploration Program.

Funding for Earth-orbital work. Efforts in Earth-orbital planetary astronomy that are associated with goals in our own solar system should be paced to the progress of the program of planetary flight missions. In order to take advantage of opportunities that present themselves internationally, or as Space Station *Freedom* develops, as well as to undertake the responsibility of ensuring that astrophysical observatories achieve their full potential for planetary astronomy, the Solar System Exploration Division should immediately seek an augmentation of funding. Under no circumstances do we envision that funds associated with the current program of research be diverted for new initiatives in Earth-orbital planetary astronomy.

The search for other planetary systems. The Planetary Astronomy Committee has evaluated the opportunities for achieving planetary science objectives by observing stellar environments and concludes that they are significant and responsive to the scientific goals of the Solar System Exploration Division. We recommend that these opportunities be pursued resourcefully by the Solar System Exploration Division, in cooperation with the Astrophysics Division. Because any program will require substantial funding, difficult choices between competing projects, and close liaison and interaction with other programs in the Office of Space Science and Applications, we recommend that a permanent working group be formed in the Solar System Exploration Division to be responsible for advice in planning and priorities in this field. We also note that this effort, because of its interdisciplinary nature, may require special nurturing from the Associate Administrator for Space Science and Applications.

Space Station Freedom: *an orbiting research laboratory offering new opportunities for planetary astronomy.*



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Summary

Planetary scientists are endowed with a powerful array of tools with which to solve the myriad puzzles of the planets, their satellites and rings, the asteroids, and the comets. If we remain on the forefront of advancing technology, and if we can attract a growing number of talented young scientists to this field, the inevitable result will be the continuing expansion of our knowledge and understanding of our astronomical neighborhood, the solar system. The remarkable variety of planetary environments discovered so far illustrates the diversity of the solar system and yields insights into its origin 4.5 billion years ago. Improved understanding of the atmospheres of the other planets will enhance our ability to grapple with problems of the fragile atmosphere of the Earth and its interactions with all our planet's ecosystems. The organic chemicals preserved in the comets and meteorites, and related chemical processes now taking place on some planetary bodies, will move us toward an understanding of the chemistry of life in the solar system and of our own connections with the dust and gas from dying stars in the Galaxy. And in the near future, the possible discovery of other planetary systems, as well as the detailed investigation of the process of star and planet formation, will permit us, for the first time, to study our planetary system in its proper cosmic context.

Our species is emerging from the cradle of its Earthly origins and is moving outward to the other planets and the stars. Planetary science is paving the path with knowledge of this new and sometimes hostile frontier, so that our first uncertain steps on other worlds can succeed in bringing us a fuller understanding of our own planet and our origins, and ultimately to the permanent preservation of humankind. Planetary astronomy has made major contributions to the initial exploration of the solar system, and we can confidently predict that its role will expand as we embrace studies not only of our own planetary system, but also of other systems orbiting other stars.

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